Volume 22 OCTOBER, 1938 Number 10

BULLETIN
of the
American Association *of* Petroleum Geologists

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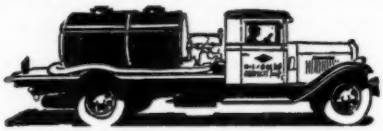

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Volume 22 Number 10

BULLETIN
of the
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

OCTOBER, 1938

SEDIMENTS OF GREAT SALT LAKE, UTAH[1]

A. J. EARDLEY[2]
Ann Arbor, Michigan

ABSTRACT

The sedimentary environment is investigated by study of the lake's origin, topography and hydrography of the region draining into the lake, chemistry of the lake waters and tributary streams, and plant and animal life in the lake. The lake is a colloidal suspension in which a concentrated electrolyte is the dispersing medium and clay the main constituent of the disperse phase. The electrolyte is a complicated solution of salts of different solubilities. Calcium and magnesium carbonate and a hydrous magnesium silicate have been precipitating out for a considerable time, and at low lake levels sodium chloride has crystallized on the bottom. Cold weather results in temporary sodium sulphate precipitation. Three types of permanent sediments are most common, namely: the clays, oölites, and calcareous algal deposits. All come from the same source materials but varying mechanical conditions or the activity of the lake plants and animals have caused different physical and chemical characteristics.

The clays are exceptionally smooth and plastic, which property is due chiefly to the base ions, particularly Na^+, absorbed by the clay particles. The average origin of the plastic sediments is approximately as follows: clastic and colloidal material transported by lake currents, 20 per cent; clastic material (possibly some colloidal) transported by wind and deposited in water, 44 per cent; and material precipitated from solution, 36 per cent.

The identifiable minerals are the common detrital ones with quartz most common. They reflect the nature of the rocks of the nearest shore, but probably contain some admixture from more distant regions by wind transportation. The chemical precipitates are aragonite, $CaCO_3$; dolomite, $2MgCO_3 \cdot CaCO_3$; parasepiolite (?), $2MgO \cdot 3SiO_2 \cdot 4H_2O$; and absorbed bases, *Ca*, *Mg*, *Na*, and *K*. A fine white colloidal clay complex is believed to be made up chiefly of colloidally transported montmorillonite (?); chemically precipitated parasepiolite (?); colloidal size particles of quartz, feldspar and other detrital minerals; and absorbed ions of *Ca*, *Mg*, *Na*, and *K*.

The average moisture content of the clays is 39 per cent on a total weight basis. Compaction and dehydration appear to be occurring even at shallow depths. A crude hexagonal fissure system is an interesting consequence at two places, as are also the effects of a recent earthquake in liberating cold salt water in fissures around an almost buried bedrock hill. The organic content of the clays averages about 1 per cent. Bacteria are very active and emit sulphurous fumes. The diagenic effect of the bacteria on the carbonate and organic content could not be determined. Careful bacteriologic work is necessary. The lake waters are reductive to iron compounds and prevent the appearance of red coloring in the sediments.

The oölites are found only along the shores exposed to vigorous wave activity. The

[1] Manuscript received, May 11, 1938.

[2] Department of Geology, University of Michigan.

oölitic sand is everywhere rippled. The oölites consist of nucleus (mineral particles and faecal pellets of the brine shrimp) and concentric layers (about 84 per cent $CaCO_3$, 5.5 per cent $2MgCO_3 \cdot CaCO_3$ and 5.6 per cent of very fine clay). The oölites grow by accretion from solution of carbonate molecules which build acicular, submicroscopic crystals of aragonite with some dolomite crystals interspersed, all probably oriented normal to the surface of attachment. The Ca^{++} and Mg^{++} ions of the carbonate crystals attract and precipitate clay particles less than 350 microns in diameter from suspension by base exchange. The clay becomes entrapped along the sides of the growing fibrous crystals. A small amount of organic matter becomes occluded in the same way. Constant agitation by the waves in the troughs of ripple marks exposes all parts of the oölite surface equally to accretion of the carbonate and clay and removes any excess clay that might settle. Radial structure is formed by inversion of aragonite to calcite with merging of crystals until microscopically visible. The enmeshed clay is pushed to the side of the growing bundles of calcite crystals or to the lamination contacts, and results in white, opaque inter-ray areas.

Extensive calcareous bioherms are present along the shores exposed to wave activity. They are principally the deposits of the alga, *Aphanothece Packardii* but bacterial precipitation of carbonate may also be important.

The $CaO:MgO$ ratio of the soluble contents of the river waters that empty into the lake is about 2.6:1. The weighted ratio of the same oxides, soluble in weak, hot HCl, from all of the lake sediments is 7.3:1. This difference can not be accounted for by continued concentration of magnesium in the lake waters, but is understood, at least in part, by base ion absorption of Mg^{++} ions in greater proportion than Ca^{++} ions in and around the various colloidal particles of the clays.

About one-third of the lake sediments are the rod-shaped faecal pellets of the brine shrimp, *Artemia gracilis*. The pellets differ in composition from the bottom clays only in a higher carbonate content indicating that the shrimps consume a great deal of inorganic matter but that some carbonate is, perhaps, precipitated in the digestive tract.

The lateral sedimentary variations and the burial of islands are described. Future structures for oil accumulation are probably in the making.

Introduction

A knowledge of sediments forming in present saline lakes should add to the ability to interpret correctly sedimentary rocks of geologic antiquity. The investigation of Great Salt Lake seemed important for this reason and a particularly opportune time occurred during the drouth of 1933 and 1934 when low lake levels exposed many square miles of lake bottom.

The sedimentary environment was established by a study of the lake's origin, chemistry, and life together with the topography and hydrography of the region draining into it. These subjects are briefly treated in the first part of the paper. The second part describes the distribution, chemistry, and petrography of the sediments, and proposes theories for their origin. To facilitate reading, a comprehensive summary of the properties and origin is included at the end of the discussion of each type of sediment. The paper concludes with a survey of the lateral variations of the sediments, the burial of the islands, and the associated structures that are in the process of formation.

The writer wishes to acknowledge his indebtedness and appreciation to the following scientists who have willingly coöperated in the work of the project: Parker D. Trask and H. E. Hammar for the

organic content analyses (the work was done under the auspices of the U. S. Geological Survey under Project No. 4, A.P.I. Research Program; actual analyses by Hammar); M. W. Senstius, University of Michigan, for mechanical analyses of the silts and clays and for many consultations regarding the chemistry of the sediments; K. A. Gorton, graduate student at the University of Michigan, for calcium and magnesium analyses of many samples; Ruth Patrick for identification and ecology of the diatoms; the late T. A. Brighton, of the University of Utah, for advice on the physico-chemical reactions in the lake; D. A. Lyon, University of Utah and chairman of the Diking Project of Great Salt Lake, for engineering data on the drillings and soundings between Promontory Point, Fremont Island, and Antelope Island, and for assistance in securing the *Hydrographer*, a well equipped boat, for study on the lake; T. C. Adams and Leon Stanley, both of the University of Utah, for hydrographic data; W. R. Taylor of the University of Michigan, and Francis Drouet of the University of Missouri, for identification of algae; W. S. Flowers, Carbon County High School, Utah, for information relative to the algae; The Southern Pacific Railroad offices in Ogden, Utah, for data compiled during the building and maintenance of the Lucin Cut-Off; Merrill Haas, who accompanied the writer on a lake trip in 1933 and assisted in collecting and recording; Max Demorest, who also accompanied the writer on a lake trip in 1934; W. F. Hunt, A. B. Peck, L. S. Ramsdell, and C. B. Slawson, of the Department of Mineralogy of the University of Michigan, for mineral determinations; and especially T. S. Lovering of the Department of Geology of the University of Michigan, W. W. Rubey and W. H. Bradley of the U. S. Geological Survey, and C. E. ZoBell of the Scripps Institution of Oceanography for critical reading. The Faculty Research Fund of the University of Michigan supplied financial assistance for an aerial survey of the lake and for some of the chemical analyses.

Sedimentary Environment

Origin of Great Salt Lake

Great Salt Lake is a saline remnant of a fresh-water body, which, at its highest level, was 1,000 feet above the present lake. It had an extreme north-south length of 300 miles, a greatest east-west extent of 180 miles, and an area of 19,750 square miles. Detailed examination furnishes evidence at once plentiful and conclusive that this ancient lake extended southward over the Sevier Desert, and probably over the Escalante Desert also, nearly to the Arizona line; westward over the Great Salt Lake Desert, into Nevada; and northward to the upper

limit of Cache Valley and, therefore, 25 miles beyond the Idaho boundary. Gilbert named this inland sea "Lake Bonneville," in honor of Captain Bonneville, who gave the first authentic description of the existing lake as a result of his explorations in 1833. Although early explorers before 1875 had observed evidence of vanished lakes, it is Grove Karl Gilbert and his associates to whom is due the greater part of the present knowledge of Great Salt Lake and its geologic history. His report, *U. S. Geological Survey Monograph I*, is the standard work on the subject. Very little new information has been added in the 48 years that have elapsed since its publication in 1890.

The Great Basin, in which Lake Bonneville and other Pleistocene lakes formed, originated some time after the beginning of extensive normal faulting. Although considerable relief may have existed in the

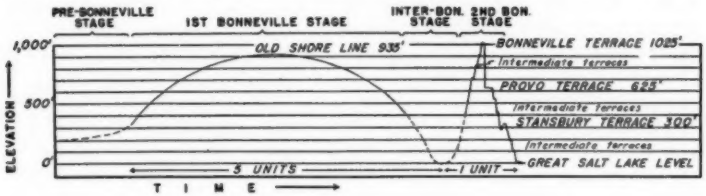


FIG. 1.—Diagram indicating fluctuations in lake level of Lake Bonneville. Adapted from Gilbert's Figure 34, p. 262, *U. S. Geol. Survey Mon. 1.*

topography at the time faulting began, drainage to the Pacific was soon cut off, and interior basins were formed. The deformation began probably in late Pliocene time[3] and has continued to the present. According to Gilbert,[4]

> Alluvial fans were formed about the bases of all its greater mountain ranges, and the smaller ranges were wholly or partly buried by valley deposits. The valley deposits may have been entirely alluvial, but were probably also partly lacustral, the lakes being of small extent . . .
>
> There followed two epochs of high water, with an interval during which the basin was nearly or quite empty. The first of these epochs was, at least, five times as long as the second. The second scored its high water mark 90 feet higher than the first [1,025 above Great Salt Lake level] and would have encroached still farther on the basin sides had it not been checked by outflow. During the epoch of outflow, the discharging current eroded the rim, and thus lowered the lake 375 feet; and after the outflow had ceased, the water fell by desiccation, with one notable interruption, to its present level in Great Salt Lake. The inter-Bonneville epoch was of greater duration than the time that has elapsed since the final desiccation . . .

[3] A. J. Eardley, "Strong Relief before Block Faulting in the Vicinity of the Wasatch Mountains, Utah," *Jour. Geol.*, Vol. 41 (1933), pp. 243–67.

[4] G. K. Gilbert, "Lake Bonneville," *U. S. Geol. Survey Monograph I* (1890), p. 316.

The final drying of the basin divided it into ten or twelve independent basins. Three of these now contain lakes, the others for the most part contain playas, or playa lakes with beds of salt.

The level of Great Salt Lake has fluctuated through a range of 15½ feet in historical time. Figure 1 is an attempt to convey a visual picture of the history of Lake Bonneville. It is an adapted reproduction of Gilbert's Figure 34, page 262.

The last outflow of the lake was at the Provo level. Desiccation resulted in the concentration of the soluble materials of the lake of this level into those of the much smaller Great Salt Lake. The soluble contents of approximately 300 parts were concentrated into one, and to this has been added the soluble discharge of the rivers since outflow ceased, leaving a lake of high salinity.

GEOGRAPHY AND TOPOGRAPHY OF GREAT SALT LAKE AREA

Great Salt Lake is divided by Promontory Range, Fremont Island, and Antelope Island into a western and an eastern basin (Fig. 2 and Pl. 1b). With the water at the highest historical level the western part would have a length of 80 miles in a northwest direction, a width of 16–24 miles, and a maximum depth of slightly less than 50 feet. The eastern division at high water extends 48 miles in a north-northwest direction, is 6–12 miles wide, and has a maximum depth of 15 feet.

Promontory Range extends southward into the lake as a peninsula more than 20 miles long. Its serrated crest in places stands 2,300 feet above Great Salt Lake but due to the aridity of the region there are no perennial streams. The canyon and gulch bottoms are dry for more than 6 months, but a few small springs issue during the entire year. Fremont Island is separated from the end of Promontory Range by a distance of 2.8 miles and from the Antelope Island by 6 miles. Antelope Island is separated from the Oquirrh Mountains on the south by a distance of 8.2 miles, when the water is at its highest stage, but during years of low lake level wagons and even light automobiles can be driven from the mainland on the southeast to the island (Pl. 2a). The Oquirrh Mountains are even higher than the Promontory Range but inasmuch as only their northern end borders on the lake, there is no direct perennial stream discharge except that coming through the concentrating plant of the Utah Copper Company.

A peninsula is almost formed by Carrington Island and Stansbury Island, which are separated by very shallow water for a distance of 4.8 miles. Stansbury Island is actually a peninsula except at very high water level. It is probably a northward extension of the Stansbury

PL. 1a.—Aerial view, looking northwest, of Carrington Island with extensive salt-crusted clay and oölitic flats laid bare by low lake level of 1936. Bird Island is just visible in northeast corner of white salt-crusted area. East margin of exposed lake bottom is chiefly bioherm.

b.—Aerial view southward, showing Lucin Cut-Off at Promontory Point, Fremont and Antelope islands, 6 and 16 miles, respectively, in distance; on right horizon, Oquirrh Range, about 40 miles away, and on left horizon, Salt Lake salient of Wasatch Range.

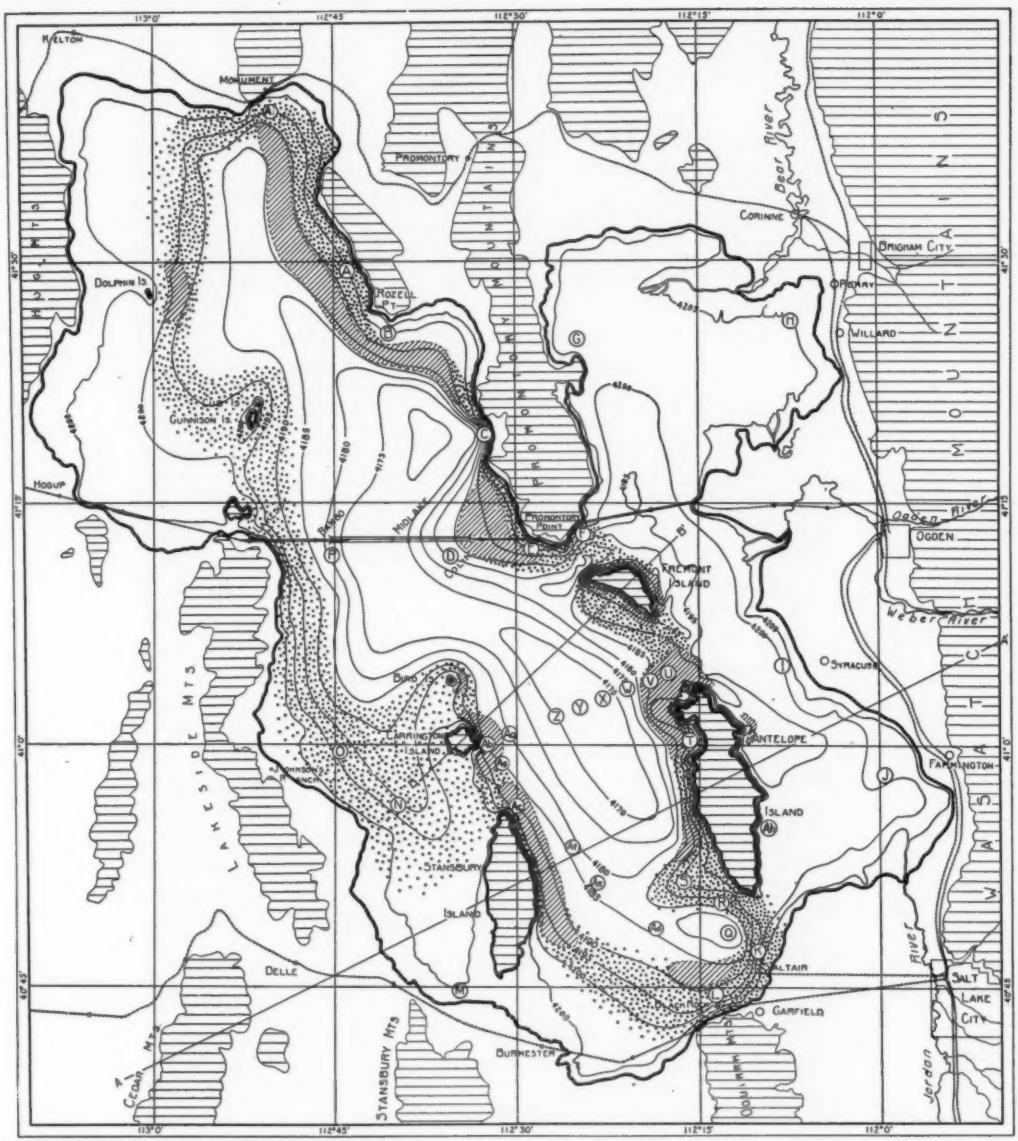


FIG. 2.—Topographic map of Great Salt Lake, showing distribution of commonest types of sediments.

Mountains. Although Antelope and Stansbury islands are often not surrounded by water, they are truly islands from a geological standpoint because they are masses of pre-Cambrian or Paleozoic bedrock surrounded by lake sediments of Pleistocene or Recent age.

The few other islands present are of much smaller size and include Gunnison, Cub, Dolphin, Bird, and Egg islands, and Black Rock (Fig. 2).

The lake is bounded on the east by the lofty Wasatch Mountains (Pl. 3a) and on the west by the Lakeside and Hog mountains (on some early maps the "Terrace Mountains") and the Great Salt Lake Desert.

Antelope and Fremont islands and the part of the Wasatch Mountains immediately east consist of pre-Cambrian crystalline rocks, principally schists, gneisses, pegmatites, and granites. The other islands and ranges mentioned are composed of Paleozoic and Algonkian(?) limestone, shale, sandstone, and quartzite. The waste products of these sedimentary rocks are fairly well mixed and form a group of clastic sediments lithologically distinct from those derived from the crystalline rocks. Their variations are given in detail in the discussion of the individual types of sediment.

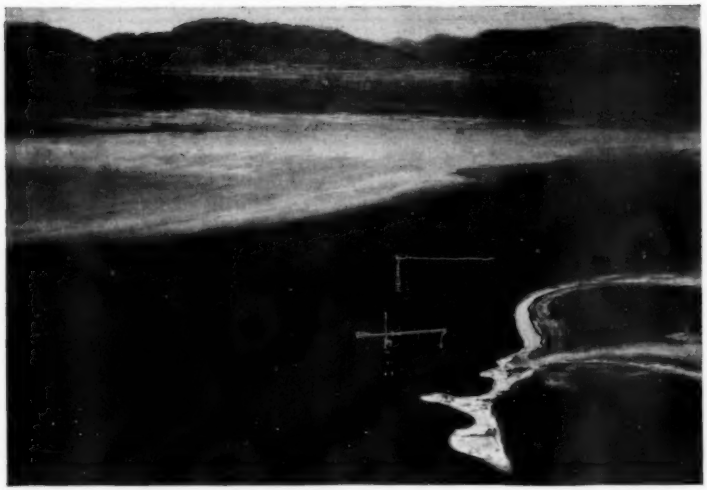
The only rivers flowing into the lake are the Bear, Weber, and Jordan rivers, which originate in the Wasatch and Uinta mountains and enter the shallow part of the lake east of Antelope and Fremont islands. There are no perennial streams entering any other section of the lake shore. A few smaller streams in the Farmington section of the Wasatch Mountains and one from the Stansbury Mountains have discharged in part into the lake but now their waters, except during floods, are appropriated for irrigation. Two artificial inflows should be mentioned, namely, the Surplus Canal and the Salt Lake City sewer outlet. These two measurable discharges, as well as features such as springs, sheet wash, and floods, are further considered under the heading, "Hydrography of Great Salt Lake."

Figure 2 is an attempt to contour the lake bottom. Most of the data have been gathered from the work of others to whom reference is made on the map itself, but the writer has supplied a number of soundings in the deeper part of the lake.

In traveling around the lake three general types of shore-line features are recognizable. There is the rugged shore-line topography whose truncated headlands or regular slopes rise fairly abruptly from the water's edge, even with the lake level at the low 1934 stage. Such shore lines are found at Rozell Point, Black Rock, parts of the west shore of Antelope Island and the east shore of Stansbury Island and

PL. 2a.—Section of Jordan River delta with south end of Antelope Island in distance. Bluff line is distinct, as well as white oölite zone. Barren alkali and salt flats in delta area are about 1–3 feet lower than plant-covered areas.

b.—Aerial view from point over Jordan River delta looking northwest, showing many distributaries. Fremont Island in distance.



PL. 3a.—Aerial view from over north end of Fremont Island looking eastward toward high Wasatch Mountains. Lake Bonneville delta with apex at mouth of Weber Canyon is conspicuous feature at base of mountains. White shore zone in middle foreground is glistening salt crust on exposed clay bottom.

b.—Aerial view over Saltair looking north at Antelope Island. Oölite beach extends from highway to slightly beyond water's edge and northward along shore up west side of Antelope Island. Exposed lake bottom east of Antelope Island is clay.

elsewhere. In such places wave activity is strong, oölitic sand is plentiful, and such features as storm beaches, bars, and sand dunes landward of the storm beaches are common (Pls. 5 and 6b).

A second type of shore line is that displayed at Farmington, Syracuse, Johnson's Ranch, and elsewhere The lake is separated from the abruptly rising bedrock masses by a wide bolson slope of coalescing alluvial fans or by a delta of old Lake Bonneville (Pl. 3a). The outer margin of the slope has such a low lakeward gradient as to appear almost a plane. It is composed chiefly of silt and fine silica sand, the latter in places drifting in low dunes. The plane is terminated lakeward by low "bluffs" ranging from 1 to 6 feet high. At the bottom of the "bluffs" the true lake bottom begins. The sediments beyond the "bluffs" are everywhere moist, if not completely saturated with lake brine, and if fine enough to draw much capillary water to the surface, a crust of glistening white salt forms. This crust is, at times, almost stout enough to bear the weight of a man walking on it, even though the underlying material be plastic almost to the degree of liquidity (Pl. 4b). Such a distinct difference exists between the material above the bluff line and that below that it is believed that the lake has not risen above this mark for a long time. All dominant shore-line features are at this level. Lakeward of the bluff line local currents in the shallow water have set up large ripple marks and irregular bars 3–12 inches in height (Pl. 3b). The bluff line (sometimes called the "meander line") is shown on the map (Fig. 2), by the heavy dark line and has generally been used as the shore line in mapping.

The bluff line is not entirely distinct along certain parts of the lake shore where another or third type of shore line is developed. Where the lake waters are remote from bed rock the alluviated basin floor is extremely flat with an almost imperceptible lakeward slope, and the water table is very close to the surface. Halophilic plants have encroached over most of the very flat area and peculiar patterns have developed such as shown in Plate 2a. The Jordan River delta (Pl. 2b) is a good example of a very gently sloping shore. On such a gradual slope the lake margins have been so shallow during all the lake-level fluctuations that in most places no decided beaches or bluffs have formed.

The bluff line approaches close to the Wasatch Mountains at Farmington on the south and at Perry and Willard on the north. In the intervening area it departs widely from the mountain front because of the great Weber River delta that was built into Lake Bonneville chiefly at the Provo level. The upper beaches of the now exposed

delta are very sandy and are poorly suited to agriculture. The peripheral part, however, constitutes one of the best fruit and truck-farming areas of the state. This is visible in the aerial photograph (Pl. 3a).

HYDROGRAPHY OF GREAT SALT LAKE

LAKE-LEVEL FLUCTUATIONS

Like all lakes that have no surface outlet or well established channels of underground discharge Great Salt Lake is subject to pronounced fluctuations in level and area. These oscillations are dependent on seasonal and yearly climatic variations unless affected by human agencies. Figure 3 is a chart showing the changes of lake

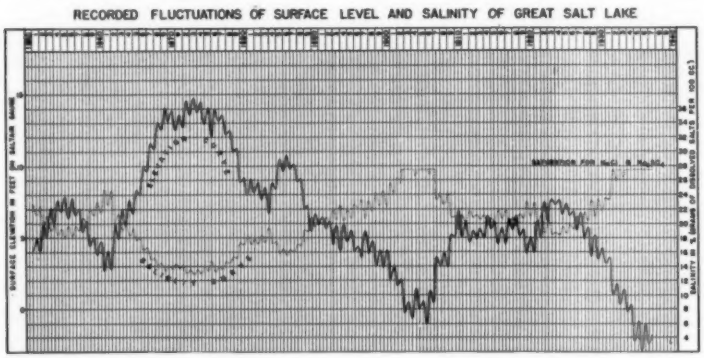


FIG. 3.—Lake-level fluctuations taken from *U. S. Geol. Survey Water-Supply Paper 517*. Zero on Saltair gauge is 4,196.8 feet above sea-level. Salinity values taken from salinity curve of Figure 4. Center line in each year column indicates July 1.

level from the earliest authentic historical observations to the present. It is adapted from Plate 2, *U. S. Geological Survey Water-Supply Paper 517*, with data of recent years supplied through personal communication with the Salt Lake City office. T. C. Adams[8] records that:

> Stage records have been constructed for the lake since 1851 and there is some fragmentary information for periods before this time. Accurate and reliable records have been continuously kept and compiled by public agencies since 1902. (The United States Geological Survey and Weather Bureau in cooperation with the Saltair Beach Company and The Southern Pacific Railroad at Saltair and Midlake, respectively). A study of the stages since 1903 shows that the lake generally reaches its seasonal low about November 1, and its seasonal high about June 1, thus requiring about seven months lowering.

[8] T. C. Adams, "Some Hydrologic Features of Great Salt Lake," *The Utah Engineer*, Vol. 6, No. 5 (1932), pp. 1–5.

However, for any one year, either the high or low date can be displaced either later or earlier by a month or a month and a half. Within the period under consideration the greatest net rise (obtained by deducting the summer lowering from the winter rise) the lake has experienced was in 1907 and attained 2.7 feet . . . The greatest net loss was in the year 1931, and was 1.9 feet. This was much greater than at any time during the last 30 years and is accounted for by the very low precipitation, the exceedingly low stream inflow, and the heat and high winds of the early summer months.

RELATION TO CLIMATIC VARIATIONS

The present climate of the region ranges from true Alpine conditions above timber line in the high Wasatch and Uinta mountains through semi-aridity at their west base to desert dryness on the west shores of Great Salt Lake. The precipitation along the eastern side of the lake ranges from 14 to 18 inches; on the western side it drops to $4\frac{1}{2}$ to 6 inches. Most of the lake's water supply arrives between February and May, inclusive.

TABLE I

CORRELATION OF INFLOW WITH SIZE OF GREAT SALT LAKE

Year	*Precipitation into Lake*	*Combined Discharge Weber River, Jordan River, Bear River, Surplus Canal*	*Unaccounted for Inflow*	*Net Change in Storage in Lake Jan. 1–Dec. 31*	*Lake Level Dec. 31*
1918	0.91	2.01	0.38	−0.45	5.3
1919	0.81	1.65	0.05	−1.34	3.9
1920	1.08	2.44	1.30	+1.12	4.3
1921	1.04	3.34	0.47	+1.37	5.5
1922	1.10	3.56	0.31	+1.16	6.4
1923	1.09	3.24	0.40	+0.93	7.3
1924	0.79	1.86	0.34	−0.81	6.5
1925	1.20	1.93	1.02	+0.35	6.7
1926	0.94	1.62	0.30	−0.94	5.6
1927	1.07	2.08	0.07	−0.58	4.9
1928	0.62	1.63	0.03	−1.47	3.8
1929	0.86	1.77	0.62	−0.45	3.4
1930	1.16	1.25	0.70	−0.55	3.2
Average	0.97	2.18	0.46	−1.66 1918–1930	2.1 drop, 1918–1930

Adapted from table, p. 5, T. C. Thomas, "Some Hydrologic Features of Great Salt Lake," *The Utah Engineer*, Vol. 6, No. 5 (1932), p. 5. All figures are in millions of acre feet.

Average discharge of Bear River at Corrine 1.56 million acre feet per year
Average discharge of Weber River at Devil's Slide 0.38 million acre feet per year
Average discharge of Ogden River at Ogden City 0.15 million acre feet per year
Average discharge of Jordan River at near Lehi 0.30 million acre feet per year
} See *U. S. Water-Supply Papers 517 and 750*

Adams has calculated an average annual evaporation of 3.3 feet from the lake's surface.[6] The greatest part of this loss is between May and September.

[6] T. C. Adams, *op. cit.*, p. 5.

The changes in level of the lake are closely correlated with the factors of inflow, precipitation, and evaporation. Their relationship is illustrated in Table I, the data for which are derived from a table prepared by Adams.[7] In its preparation he found the following factors of significance.

1. The amount of water that is evaporated each year depends upon the area and concentration of the water, both of which are determined by the level of the lake. For each foot of change in level within the normal range there is a change in area of about $2\frac{1}{2}$ per cent and a change in concentration of about 1 per cent. The rate of evaporation varies inversely as the concentration so that at average lake-level evaporation from the brine is one-fourth less than from a body of fresh water of similar area. Diminishing lake area and increasing concentration retard evaporation so effectively that the loss from the lake during years of lowest level (1905 and 1934) is approximately one-half that of years of highest level (1869 to 1875). The total annual loss of water from the lake averages 3.7 million acre-feet.

2. Inflow into the lake is of two classes, namely, measured inflow and unmeasured inflow. Measured inflow is that of the Bear, Weber, and Jordan rivers and the Surplus Canal. "Unmeasured inflow" ("Unaccounted inflow" in Table I) may be of four classes: (1) deep percolation into the lake from perennial springs and general seepage over indefinite areas; this kind of inflow is unimportant; (2) seepage or underflow that follows underground channels which offer little resistance because of their high permeability or shortness, allowing the water to enter as ephemeral springs or through seep areas that would be dry much of the year if above the surface of the lake; this is also believed unimportant; (3) the general sheet of surface water that flows broadcast over the gently sloping riparian lands after periods of heavy precipitation or when the winter snow is melting in the spring; (4) normal streams of small size for which no discharge records are available.[8]

3. The only way water leaves the lake is through evaporation. The imperviousness of the lake sediments, as the present study reveals, substantiates this premise.

THERMAL CONDITION OF LAKE WATERS

The thermal condition of the lake waters was investigated for the first time, as far as the writer knows, on September 5, 1934. The temperature gradient was observed three times in different deep

[7] *Ibid.*, p. 5.

[8] T. C. Adams, *op. cit.*, pp. 1–2.

parts of the lake with a Tycos maximum-minimum thermometer, Max Demorest making the readings. An upper zone about 6 feet thick was on this day 1°–2°C. warmer than the lower zone which remained constant in temperature from 6 feet to 30 feet. The data collected are given in Table II. The lack of thermal stratification of the lake waters is indicative of complete and constant circulation.

TABLE II

TEMPERATURE GRADIENT OF GREAT SALT LAKE WATERS
(September 5, 1934)

Depth in Feet	*Station Ad** 12:45 P.M.	*Station Ae* 3:25 P.M.	*Station Af* 6:10 P.M.
0	26.5°C.	27.5°C.	26.8°C.
3	26.3	27.0	26.5
6	25.8	26.5	25.7
12	25.5	25.8	25.7
18	25.5	25.8	25.7 (Bottom)
24	25.5 (Bottom)	25.8 (Bottom)	

* See Figure 2 for location of stations.

Due to the shallowness of the lake (deepest parts 27–30 feet on September 5, 1934) surface drift, undertow, and wave activity keep the waters well mixed.

CHEMISTRY OF GREAT SALT LAKE

SALINITY

The salinity of Great Salt Lake varies inversely as the lake volume. It has been found to range from 13.8 per cent in 1877 when the lake stood at 13.5 feet (Saltair gauge) to 27.6 per cent in 1935 when it stood at 2.0 feet below the zero mark. The waters become saturated for $NaCl$ and Na_2SO_4 at approximately zero elevation on the Saltair gauge. This is shown in Figure 4. The saline content changes, therefore, at the rate of about 1 per cent for each foot change in stage. The few salinity analyses available were plotted and the resultant curve (Fig. 4) is believed to be a fair approximation of the salinity variation of the lake, although one of the analyses departs widely from the curve and is probably somewhat in error. The curve is the basis of the annual salinity curve of Figure 3. It shows the salinity to increase rapidly as the lake falls below the 2-foot mark (Saltair gauge) until a level of zero gauge feet is attained when the saturation point for $NaCl$ and Na_2SO_4 is reached. As the lake falls below zero gauge elevation the salinity increases very slightly due to the further concentration of the mother liquors, that is $MgCl_2$ and KCl, while $NaCl$ and Na_2SO_4 precipitate out.

The total salt content in the lake has been estimated as slightly more than 6 billion tons.[9]

COMPOSITION OF LAKE WATER

Table III taken from Clarke[10] shows in detail the composition of the lake waters. Although the salinity of the lake ranges from 4 to 10

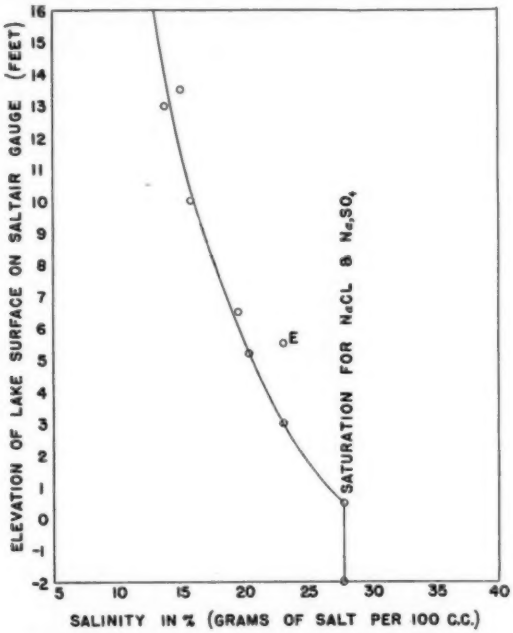


FIG. 4.—Salinity curve of Great Salt Lake. Values taken from Table III. Analysis E is apparently wrong and was not given weight in finding best representative curve. Salinity of saturation point for $NaCl$ and Na_2SO_4 was determined by K. A. Gorton, Department of Geology, University of Michigan.

times that of the ocean its saline matter has nearly the same composition. The very low percentage of the carbonates, particularly of calcium, and the higher sodium and lower magnesium percentage are the only conspicuous variations from the oceanic standard. Clarke concludes that the "general similarity, the identity of type, is unmistakable."[11]

[9] T. C. Adams, *op. cit.*, p. 5.

[10] F. W. Clarke, "Data of Geochemistry," *U. S. Geol. Survey Bull. 770* (1924), p. 157.

[11] *Ibid.*, p. 176.

TABLE III

ANALYSES OF WATER FROM GREAT SALT LAKE[1]

	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*
Cl	55.99	56.21	55.57	56.54	55.69	55.25	55.11	55.48
Br	Trace	—	—	—	Trace	Trace	—	—
SO_4	6.57	6.89	6.86	5.97	6.52	6.73	6.66	6.68
CO_3	—	.07	—	—	—	—	—	.09
Li	Trace	—	—	—	.01	Trace	—	—
Na	33.15	33.45	33.17	33.39	32.92	34.65	32.97	33.17
K	1.60	(?)	1.59	1.08	1.70	2.64	3.13	1.66
Ca	.17	.20	.21	.42	1.05	.16	.17	.16
Mg	2.52	3.18	2.60	2.60	2.10	.57	1.96	2.76
Fe_2O_3, Al_2O_3, SiO_2	—	—	—	—	.01	—	—	—
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Salinity, per cent	14.994	13.790	15.671	19.558	†23.036	27.72	22.99	20.349

† More correctly, 230.355 grams per liter.

[1] Reproduced from Clarke's "Data of Geochemistry," *U. S. Geol. Survey Bull. 770* (1924), p. 157.

A. By O. D. Allen, *Rept. U. S. Geol. Expl. 40th Par.*, Vol. 2(1877), p. 433. Water collected in 1869. A trace of boric acid is also reported, in addition to the substances named in the table. Allen also gives analyses of a saline soil from a mud flat near Great Salt Lake. It contained 16.40 per cent of soluble matter much like that of the lake water.

B. By Charles Smart. Cited in *Resources and Attractions of the Territory of Utah* (Omaha, 1879). Analysis made in 1877.

C. By E. von Cochenhausen, for C. Ochsenius, *Zeit. Deutsch. Geol. Gesell.*, Vol. 34 (1882), p. 359. Sample collected by Ochsenius, April 16, 1879. Ochsenius also gives an analysis of the salt manufactured from the water of Great Salt Lake.

D. By J. E. Talmage, *Science*, Vol. 14 (1889), p. 445. Collected in 1889. An analysis of a sample taken in 1885 is also given.

E. By E. Waller, *School of Mines Quar.*, Vol. 14 (1892), p. 57. A trace of boric acid is also reported.

F. By W. Blum. Collected in 1904. Recalculated to 100 per cent. Reported by Talmage in *Scottish Geog. Mag.*, Vol. 20 (1904), p. 424. An earlier paper by Talmage on the lake is in the same journal, Vol. 17 (1901), p. 617.

G. By W. C. Ebaugh and K. Williams, *Chem. Zeitung*, Vol. 32 (1908), p. 409. Collected in October, 1907.

H. By R. K. Bailey, in the laboratory of the U. S. Geological Survey. Sample collected by H. S. Gale, October 24, 1913.

The writer believes that considerable of the saline matter of Great Salt Lake was leached first, from deposits of oceanic salt of Jurassic age which crop out extensively in Sanpete Valley within the Great Salt Lake drainage area and second, from the soils derived in turn from the sedimentary, igneous, and metamorphic rocks of the drainage area of the lake. It has long been recognized that waters percolating through the soil partly separate the more diffusible alkaline chlorides from the less soluble calcium and magnesium salts so that the alkaline chlorides reach the lake reservoir in larger quantities. The relationship of Great Salt Lake as a "saline" type lake to the ocean is emphasized by Clarke when he discusses an opposite type, namely, the "alkaline" lake which is high in carbonates and representative of volcanic regions. The saline type is low in carbonates and is associated with sedimentary rocks. There are extensive outcrops of igneous rocks in the region, and although they are of minor importance when their areal distribution is compared to that of the

sedimentary rocks they probably have had some influence on the composition of the lake's water.[12]

COMPOSITION OF TRIBUTARY RIVER WATERS

For the soluble contents of the waters tributary to Great Salt Lake several analyses are available (Table IV). All the rivers tributary to Great Salt Lake carry notable quantities of carbonates and are such as to be known as normal carbonate waters in contrast to the saline water of the lake itself.

TABLE IV

ANALYSES OF WATERS TRIBUTARY TO GREAT SALT LAKE[1]

	A	*B*	*C*	*D*	*E*	*F*	*G*
Cl	2.68	32.36	35.54	34.76	5.38	23.21	13.73
SO_4	5.76	8.16	26.54	30.68	2.87	5.65	9.25
CO_3	52.68	21.53	2.67	Trace	52.57	33.68	40.00
Na	4.49	20.54	26.13	23.04	3.74	11.31	8.37
K						4.16	4.19
Ca	23.69	10.12	7.59	10.26	24.19	16.05	18.19
Mg	6.86	4.76	1.53	1.26	7.15	5.94	6.27
SiO_2	3.84				3.69		
$(Al, Fe)_2O_3$		2.53			.41		
	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Salinity, parts per million	185	637	892	1,090	243	444	455

[1] Reproduced from Clarke's "Data of Geochemistry," *U. S. Geol. Survey Bull. 770* (1924), p. 158. The analyses are all reduced to standard form with bicarbonate radicals recalculated to normal CO_3.

A. Bear River at Evanston, Wyoming. Analysis by F. W. Clarke, *U. S. Geol. Survey Bull. 9* (1884) p. 30.

B. Bear River at Corinne, Utah, near its mouth. Analysis received from the Southern Pacific Railroad.

C. Jordan River at intake of Utah and Salt Lake canal. Analysis by F. K. Cameron, *U. S. Bur. Soils Rept. 62* (1900), p. 108.

D. Jordan River near Salt Lake City. Analysis by F. K. Cameron, *op. cit.*

E. City Creek, Utah. Analysis by T. M. Chatard, *U. S. Geol. Survey Bull. 9* (1884), p. 29.

F. Ogden River at Ogden, Utah.

G. Weber River at mouth of canyon. Analyses *F* and *G* made under the direction of F. K. Cameron, Field Operations Division Soils, U. S. Dept. Agri., 1900, p. 226.

CHEMICAL PRECIPITATES IN GREAT SALT LAKE

Sequence of salt precipitation.—Many analyses of the various types of sediments of Great Salt Lake have been made (pp. 1343, -57, -84, and -87) and they all show a large $CaCO_3$ and $MgCO_3$ content. For some time past carbonate precipitation has been the outstanding chemical process. By September 5, 1934, when the lake level had fallen to 1.4 feet below zero on the Saltair gauge, the lake bottom had become encrusted with a layer of coarsely crystalline halite (*NaCl*) 1–6 inches in thickness. The individual hopper-shaped crystals, both square and rectangular, were ¼–1½ inches across. The water was milky white with exceedingly fine crystals of Glauber salt, or mirabilite

[12] The significance of volcanic eruptive rocks in the Great Salt Lake Basin is considered under the heading, "Chemical Precipitates in Great Salt Lake."

($Na_2SO_4 \cdot 10H_2O$), which seemed to hang in suspension indefinitely. Where salt-water spray wetted a surface, crusts of mirabilite formed. These deposits remained moist because of the deliquescence of the salt.

The growing halite crystals were free of mirabilite as shown by a $BaCl_2$ test for sulphate. In years past mirabilite has precipitated out during the winter months only to be re-dissolved when the water became warm in the spring and early summer.

The sequence of salt precipitation in Great Salt Lake is similar to, but not identical with, the sequence generally ascribed to a body of marine water during its desiccation. Following the precipitation of the difficultly soluble carbonates of calcium and magnesium the slightly soluble anhydrite (sometimes gypsum) will be thrown down, to be succeeded by sodium chloride. Remaining in the last bitterns are the chlorides and sulphates of magnesium, potassium, and perhaps sodium, which are deposited as complex mineral compounds upon complete evaporation. In Great Salt Lake mirabilite precipitates with or after the carbonate but the common sulphate, anhydrite, does not form as might be expected. This is because of a deficiency of calcium ions in the lake waters. Considerable sodium carbonate and carbonic acid were discharged into the lake by streams draining areas of eruptive rocks in the region,[13] and calcium, in solution as the chloride, probably was precipitated as the carbonate according to an equation such as the following.

$$CaCl_2 + Na_2CO_3 = CaCO_3 + 2NaCl$$

To predict the sequence of salt or mineral deposition during complete evaporation of Great Salt Lake would be a problem far from simple as the foregoing paragraphs suggest. A phase-rule study of the Great Salt Lake brine, such as was made by Teeple[14] on the salts and brine of Searles Lake, would be necessary. Much of the critical data of Teeple's report would undoubtedly apply to the conditions obtaining in the Great Salt Lake brines, but his data are not directly applicable to the Great Salt Lake. The problem is beyond the scope of the present report, but a beginning has been made by W. D. Bonner of the University of Utah.

Calcium and magnesium carbonate precipitation.—As calcium and magnesium carbonates have been the chief permanent chemical deposits on the lake bottom the mechanism of such precipitation is of

[13] F. W. Clarke, *op. cit.*, p. 179.

[14] John E. Teeple, "The Industrial Development of Searles Lake Brines with Equilibrium Data," *Amer. Chem. Soc. Mon. Ser. 49* (1929).

interest. The most important factors influencing $CaCO_3$ solubility and precipitation in the lake are: the amount of CO_2, $NaCl$, and Na_2SO_4 in the water; evaporation; algae photosynthesis, and bacterial metabolism. Other factors, either minor or local, include temperature changes, atmospheric pressure changes, under- and super-saturation, size of particles of the solid phase, crystal form of the solid phase, and the breaking down of the metastable bicarbonate molecule by wave agitation.

As the concentration of CO_2 determines the amount of $CaCO_3$ that can be changed to the more soluble bicarbonate, $Ca(HCO_3)_2$, the absorption or elimination of this gas may cause solution or precipitation or $CaCO_3$. That CO_2 is less soluble in $NaCl$ and Na_2SO_4 solutions than in fresh water is well known and it would seem to follow that the normal carbonate stream waters entering the brine of Great Salt Lake would lose part of their CO_2 content and the precipitation of $CaCO_3$ which had been held in solution as the bicarbonate would result.

TABLE V

SOLUBILITY OF CARBON DIOXIDE IN WATER, SODIUM CHLORIDE SOLUTION, AND VARIOUS CONCENTRATIONS OF GREAT SALT LAKE WATER, AT 0° AND 25°C.

Lake Level in Feet	*Salinity (Grams per 100 Cc.)*	*Density*	*Coefficient of Absorption*			
			Great Salt Lake Water		*Pure NaCl Solution*	
			0°C.	*25°C.*	*0°C.*	*25°C.*
15	15.13	1.104	0.887±.005	0.418±.005		
6.2	23.98	1.159	0.614±.005	0.338±.005	0.678	0.352
−1.2	27.6 (Saturated)	1.224	0.440±.01	0.263±.01		
Distilled water			1.713	0.759		

The coefficient of absorption figures are unit volumes of gas absorbed in a unit volume of solution. The figures for the $NaCl$ solution are those for a 3.44 normal solution which corresponds in gram equivalents of Na to Great Lake water of 23.98 per cent salinity. H_2O and $NaCl$ solution data taken from Chr. Bohr, "Definition und Methode zur Bestimmung der Invasions- und Evasionscoefficienten bei der Auflösung von Gasen in Flüssigkeiten," *Annalen der Physik und Chemie*, Neue Folge, Vol. 68 (1899), p. 500. Great Salt Lake analyses by K. A. Gorton, University of Michigan. The pH of Great Salt Lake water ranges from 7.4, when saturated with $NaCl$ and Na_2SO_4, to 8.48, when diluted with 6 to 7 parts of water (manuscript by W. D. Bonner, University of Utah, 1937).

Table V shows the solubility of CO_2 in various solutions to be affected as strongly by a 25°C. change in temperature as by doubling the salinity. It indicates that pure water can absorb four times as much CO_2 as can the Great Salt Lake brine when saturated with $NaCl$ and Na_2SO_4.[15] It indicates also that the brine is less absorbent

[15] W. D. Bonner has found that the actual amount of CO_2 dissolved in the lake water (the salinity is not given) is about half as much as pure water would dissolve. Manuscript, University of Utah (December, 1937).

than a gram-molar solution of pure $NaCl$. The reaction for either calcium or magnesium might be written as follows.

$$\begin{array}{lll} & & CO_2 \text{ (in air)} \\ & & \Downarrow\Uparrow \\ & & H_2O+CO_2 \text{ (in water)} \\ & & \Downarrow\Uparrow \\ Ca(HCO_3)_2 & CaCO_3+H_2CO_3 & (1) \\ & \text{(solid)} \quad \Downarrow\Uparrow & \\ & CaCO_3 \quad H^++HCO_3^- & (2) \\ & \text{(in solution)} \quad \Downarrow\Uparrow & \\ & Ca^{++}+CO_3^{--} \quad H^++CO_3^{--} & (3) \end{array}$$

With the removal of CO_2 from the solution, some of the H_2CO_3 would necessarily break up into H_2O and CO_2 to supply the deficiency of CO_2 thus created. In turn, some of the ions of stage (2) would unite to form molecular H_2CO_3. To supply the HCO_3^- ions taken from stage (2), the ions of stage (3) would unite, thus removing CO_3^{--} ions from the solution. Inasmuch as these CO_3^{--} ions are attracted as much by the Ca^{++} ions as the H^+ ions, some of the ionized $CaCO_3$ will revert to the molecular condition and hence into the solid state as a precipitate.

The strong solution of electrolytes of the lake water should cut down the CO_2 content of the river waters entering the lake and $CaCO_3$ should be precipitated unless the salts in solution in the brine offset this loss by increasing the solubility of $CaCO_3$. The same principle would apply to $MgCO_3$ precipitation.

The solubility of $CaCO_3$ in solutions of $NaCl$ and Na_2SO_4 agitated in laboratory air should give results applicable to the brine of Great Salt Lake. In Table VI data from the work of Pia[16] reveal an unexpected increase of $CaCO_3$ solubility with increasing salinity—the opposite effect of that anticipated from the CO_2 absorption experiment. With increasing salinity the solubility of CO_2 decreases but the "salting-out" effect of the brine for the CO_2 from the bicarbonate river waters is of incidental importance. This observation is discussed in some detail by Pia[17] to whom the reader is referred for further information.

On the other hand Revelle, of the Scripps Institution of Oceanog-

[16] Julius Pia, "Die Binnengewässer," *Kohlensäure und Kalk*, Band 13 (1933), p. 70, Table 28. E. Schw. Verlagsbuchhandlung, Stuttgart.

[17] *Ibid.*, pp. 81–91.

raphy,[18] finds that the most important factor controlling the solubility of $CaCO_3$ in sea water is the CO_2 content of the water. Temperature and salinity are less important factors. Revelle did not deal with the great salinity concentrations found in Great Salt Lake and the salinity changes in the ocean evidently do not assume the controlling rank that they do in Great Salt Lake.

The rivers are the perennial contributors of $CaCO_3$ to the lake and the problem of the reaction of their waters with those of the lake has already been suggested: is the $CaCO_3$ precipitated during the season of maximum river discharge—February to May—or does the precipitation lag until the season of maximum evaporation—June to November?

The calcium and magnesium carbonate content of the measured and analyzed discharge into Great Salt Lake is shown in Table IV. The paucity of analyses in general, the variability of the Jordan River analyses, and the effect of irrigation in changing the salt and carbonate content of the rivers since the region has been settled and farmed, render the average figure, 173 parts of $CaCO_3$ per million, only an approximation. This figure was derived by properly weighting the volume discharge of each stream represented by chemical analysis. It is believed to vary less than 50 per cent from the amount that existed in the stream waters for 2,000 or 3,000 years prior to human occupation.

Frear and Johnston[19] conclude that in pure water under a normal CO_2 partial pressure of 0.00032 atmosphere (amount in air) 53 parts per million of $CaCO_3$ may be dissolved. Before the streams reach the lake in flowing over the "alkali flats" they pick up considerable salt (Table IV) thus increasing the solubility of $CaCO_3$. Some CO_2 might also have been introduced by decaying organic matter. The increased ability to dissolve $CaCO_3$ is shown by the figure, 173 parts per million, which is more than three times as much as 53. The average "freshwater" stream discharge must be nearly saturated with $CaCO_3$.

The waters of Great Salt Lake with a salinity of 20.35 per cent contain approximately 305 parts per million of $CaCO_3$ (see sample H, Table III, temperature not given) with which they must be saturated as they are everywhere in contact with the solid phase on the lake bottom which has been precipitating out profusely for some time past.

It will then be assumed that the tributary streams and the lake

[18] Roger Revelle, "Physico-Chemical Factors Affecting the Solubility of Calcium Carbonate in Sea Water," *Jour. Sed. Petrol.*, Vol. 4, No. 3 (1934), p. 103.

[19] Frear and Johnston, cited by Julius Pia, *op. cit.*, p. 70, Table 28.

are both saturated with $CaCO_3$ under the same atmospheric pressure and at the same temperature. Great Salt Lake is much more saline than the fresh-water streams and, therefore, holds about 305 parts per million of $CaCO_3$ to the latter's 173. When the two solutions are mixed the resultant solution contains amounts of the various salts in direct proportion to the percentage of each solution used. However, the solubility of $CaCO_3$ is not necessarily directly proportional to the amount of dilution or concentration that occurs. If two curves are constructed from Table VI showing the solubility of $CaCO_3$ as the

TABLE VI

SOLUBILITY OF CALCIUM CARBONATE IN SODIUM CHLORIDE AND SODIUM SULPHATE SOLUTIONS

NaCl in 1 L. Solution Grams	*$CaCO_3$ in 1 L. Solution Mg.*	*Na_2SO_4 in 1 L. Solution Grams*	*$CaCO_3$ in 1 L. Solution Mg.*
0.000	64.6*	0.000	57.1*
9.720	109.3	2.800	91.9
21.010	126.7	5.235	106.7
30.301	132.9	11.730	143.8
50.620	139.1	36.860	200.0
69.370	136.7	74.010	244.5
98.400	134.2	116.100	282.5
147.400	121.7	184.200	347.6
234.500	96.9	213.700	364.9
262.300	75.8	255.900	410.5

The solutions are in equilibrium with laboratory air, the *NaCl* solution at 25°C. and the Na_2SO_4 at 24°C. After Cameron and Seidell, 1902. Data taken from Pia's compilations, p. 83, *op. cit.*

* The difference in these two figures is a result of variable determinations of the saturation point which is difficult to establish principally because of supersaturation.

concentration of *NaCl* and Na_2SO_4 increases and from these a third curve is drawn giving *NaCl* 9 points weight and 1 point weight to Na_2SO_4 (the approximate ratio in Great Salt Lake), the solubility of $CaCO_3$ in a solution having the approximate composition of Great Salt Lake waters at various concentrations will be obtained. This curve, if not entirely accurate, must approximate one obtained by direct laboratory determination of the $CaCO_3$ solubility in Great Salt Lake water. The curve is conspicuously convex in the direction of increasing $CaCO_3$ solubility (Fig. 5). This indicates that the mixing of the two solutions results in less $CaCO_3$ present at any concentration than is soluble, and that no precipitation occurs as the rivers discharge into the lake.

When through evaporation the lake level returns each year to the position it held before the spring discharge of the river waters, an excess $CaCO_3$ content results and must eventually be precipitated. As evaporation reaches a maximum between June and November the

greatest deposition occurs during this time. The absence of localized calcium carbonate deposition in the eastern part of the lake around the river mouths and the somewhat uniform distribution over the entire western part appear to substantiate this view of carbonate precipitation during the season of greatest evaporation. Time for circulation and mixing of the lake waters after the spring run-off is thus provided.

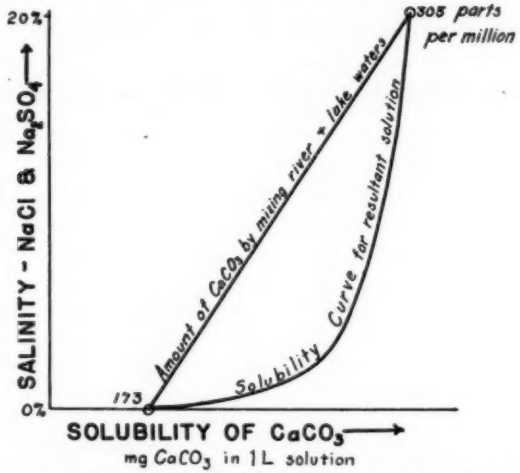


FIG. 5.—Curves showing amount of $CaCO_3$ present and solubility of $CaCO_3$ as river waters become mixed with lake brines.

The algae[20] living in the lake have built extensive deposits of lime rock (see p. 1379). The physiological process of photosynthesis causes the extraction of CO_2 from the water around the algae, thus decreasing the solubility of $CaCO_3$ and resulting in its subsequent precipitation. The subject is treated at length on pages 1376–84. The wide areal distribution of the deposits (Fig. 2) indicates the importance of the process.

The lake water even at its highest salinity supports a rich indigenous bacterial flora, according to C. E. ZoBell[21] and it is possible that the bacteria play an important rôle in carbonate precipitation, and may also have contributed to the algal deposits. Quoting from ZoBell's communication,

[20] Seville Flowers, "Vegetation of the Great Salt Lake Region," *Bot. Gaz.*, Vol. 95 (1934), pp. 353–419.

[21] Personal communication, Scripps Institution of Oceanography.

. . . the bacterial flora in the presence of organic matter has a tendency to increase the alkalinity by the production of ammonia. Most of the bacteria are periphytes which grow only when attached to some solid surface. This characteristic has a tendency to localize their activities in a relatively small focus so they could appreciably change the pH of the medium in their immediate vicinity without perceptibly altering the reaction of the surrounding medium. Our laboratory experiments conclusively demonstrate that the bacteria of the lake can change the reaction sufficiently to precipitate carbonates but we have no field observations to prove that they do.

Rate of carbonate deposition.—The rate of $CaCO_3$ precipitation may be computed when the two factors of annual inflow and lake-bottom area covered by the lime deposits are known. These are as follows.

The average annual discharge of water is 3,610,000 acre-feet (Table I). The average $CaCO_3$ content of the discharge is 173 parts per million (p. 1326). The area of the lake bottom at the zero stage (Saltair) is 1,024,000 acres.

Therefore:

Volume in acre-feet × weight in lbs. × per cent $CaCO_3$ = amount deposited annually.

Substituting figures:

$$3{,}610{,}000 \times (62.3 \times 43{,}560) \times .000173 = 14{,}371{,}088{,}900 \text{ lbs. } CaCO_3.$$

Also:

$$\frac{\text{Annual discharge in lbs.}}{\text{Area of lake in sq. ft.}} = \text{lbs. per sq. ft. of carbonate deposited annually.}$$

Substituting figures:

$$\frac{14{,}371{,}088{,}900}{1{,}024{,}000 \times 43{,}560} = .038 \text{ lb. per sq. ft.}$$

The chemical precipitates in the lake (pp. 1356–59) that form part of the plastic clays are complex and consist probably of three crystalline compounds, $CaCO_3$, $2MgCO_3 \cdot CaCO_3$, and $2MgO \cdot 3SiO_2 \cdot 4H_2O$. Hence, all of the Ca and CO_3 does not precipitate as $CaCO_3$. When the "rate of $CaCO_3$ precipitation" is computed, therefore, it is not the rate of true $CaCO_3$ (aragonite), or the rate of total carbonate (aragonite plus dolomite), but it is a useful figure with which to compute the rate of total clay accumulation (p. 1410).

The greater the compaction of the carbonate precipitate the thinner the annual accumulation will be. This ratio has been computed in inches and is shown in Table VII.

TABLE VII

RATE OF SEDIMENTATION IN GREAT SALT LAKE

Per Cent Porosity	Moisture Per Cent by Weight	Sp. Gr. Dry	Sp. Gr. Wet	Increment of $CaCO_3$ Deposition Per 10,000 Years			Increment of Total Sediment Deposition Per 10,000 Years		
				Feet	Inches	Centimeters	Feet	Inches	Centimeters
5	1.9	2.56	2.61	2	4.6	72.6	6	3.8	191.0
20	8.5	2.16	2.36	2	9.9	86.1	7	2.0	226.6
50	27.0	1.35	1.85	4	6.2	137.7	11	10.7	362.4
65	41.0	0.95	1.6	6	5.2	194.7	16	10.8	512.4

The figures are for the lake as a whole. All types of sediments were weighted on the basis of their areal distribution: clays, 70 per cent; oölites, 20 per cent; bioherms, 10 per cent. The average $CaCO_3$ content on this basis is about 38 per cent. For different degrees of compaction the increment of accumulation per 10,000 years ranges as shown.

LIFE IN GREAT SALT LAKE

The intense salinity of Great Salt Lake is not favorable to the existence of the ordinary aquatic forms of life, and adaptations to the brine are evidently rare. Most of those few forms of life, however, that have accustomed themselves to the lake waters are very abundant.

Among the macroscopic forms of greatest significance to the sediments are the *abundant* brine shrimp, *Artemia gracilis*, and the blue-green alga, *Aphanothece packardii*. At times the brine shrimps "congregate in such numbers as to tint the water over wide areas. They are found in the lake at all seasons but are most numerous between May and October."[22] The eggs of the brine shrimp were numerous during the summer of 1934 when high salt concentrations prevailed. The algae are exceedingly abundant as attested by the extent of the bioherms which they build (Fig. 2). They are not only attached to the calcareous deposits but many break loose and drift before the wind in long, irregular streams on the lake surface. These commonly accumulate along the shore and in decaying contribute to the characteristic fetid odor of the lake-shore facies. During certain years the puparia of the fly *Ephydra* have been known to drift upon the shore in long windrows and countless swarms of the adult flies have often been seen resting on the surface of the water or flying up at will. They drop their eggs freely in the water.[23]

Up to the time of the present study investigators have reported 9 or 10 species of animals and nearly a hundred species of plants in the lake. Of the animals, 1 is a crustacean, 3 are flies, 5 or 6 are proto-

[22] J. E. Talmage, *The Great Salt Lake, Past and Present* (1900), p. 68. Published and sold by Deseret Book Store, Salt Lake City.

[23] C. J. Vorhies, "Notes on the Fauna of Great Salt Lake," *Amer. Naturalist*, Vol. 51 (1917), p. 496.

zoans. Of the plants that have been listed 13 species are algae, 12 are bacteria, and 62 are diatoms. It is extremely doubtful that all the species identified live and reproduce in the brine because certain forms are tolerant of the lake water and others are fresh-water species that have been carried into it and preserved. For instance, 24 genera and 62 species of diatoms were identified by Ruth Patrick[24] of Temple University from lake-bottom samples of clay collected by the writer and she finds that none of these is established in the brine itself but lives and reproduces in springs, creeks, and marshes tributary to the lake. Kirkpatrick[25] has suggested that the final way of determining the species that normally inhabit the lake water is by growing them in cultures during a period of time, long enough to eliminate any forms that may have come from extraneous sources. She cultured the lake algae during a prolonged period and could only be sure that 5 colonial forms of blue-green algae were present in contrast to 13 previously described.

ZoBell and Smith[26] attacked the problem of the bacteria in the lake in much the same way and found that, although some were halophyllic tolerant contaminants, a rich bacterial flora was truly indigenous. Daines[27] as early as 1917 declared there was a rich bacterial flora in the bottom clays. ZoBell's counts show the bacteria to range from less than ten to a few hundred per cubic centimeter of lake water and from a few hundred to several hundred thousand viable bacteria per wet gram of lake-bottom clay.

A list of the species from Great Salt Lake as described by various authors is as follows, most of the information having been compiled from Kirkpatrick's thesis.

1869. *Artemia fertilis* (or *gracilis*) Verril. A. E. Verril, *Twelfth Annual Rept., U. S. Geol. and Geog. Survey of the Territories of Wyoming and Idaho*, Part 1 (1878), p. 330.

1871. *Ephydra gracilis* Packard. A. S. Packard, Jr., "On Insects Inhabiting Salt Water," *Amer. Jour. Sci.*, Vol. 1 (1871), pp. 100–10.

1879. *Polycystis packardii, Ulva marginata* ag., and *Rhizoclonium salinum* Ktz. A description of a blue-green alga, *Polycystis packardii*. A. S. Packard, Jr., "The Sea-Weeds of Great Salt Lake," *Amer. Nat.*, Vol. 13 (1879), pp. 701–03. Description by W. G. Farlow.

[24] Ruth Patrick, "Some Diatoms of Great Salt Lake," *Bull. Torrey Bot. Club*, Vol. 63 (1936), pp. 157–66.

[25] Ruth Kirkpatrick, *The Life of Great Salt Lake with Special Reference to the Algae.* Thesis submitted to the University of Utah, May, 1934.

[26] C. E. ZoBell, D. Q. Anderson, and W. W. Smith, "The Bacteriostatic and Bactericidal Action of Great Salt Lake Water," *Jour. Bacteriology*, Vol. 33, No. 3 (1937), pp. 253–62.

[27] L. L. Daines,* "On the Flora of Great Salt Lake," *Amer. Naturalist*, Vol. 51 (1917), pp. 499–506.

(* Incorrectly printed as Daniels.)

1891. *Ephydra gracilis*. E. A. Schwarz, "Preliminary Remarks on the Insect Fauna of Great Salt Lake," *Can. Ent.*, Vol. 23 (1891), pp. 235–41.
1892. *Gloeothece* and *Gloeocystis*. A. Rothpletz, "On the Formation of Oölite," *Bot. Centrbl.*, Vol. 51 (1892), pp. 265–68.
1892. *Gloeocapsa* and *Gloeothece*. *Idem*, "On the Formation of Oölite," *Amer. Geol.*, Vol. 10 (1892), pp. 279–82.
1898. *Aphanothece utahensis*, *Polycystis packardii*, *Dichothrix utahensis*, *Enteromorpha marginata*, *Enteromorpha tubulosa*, *Chara contraria*. Josephine Tilden, "American Algae," *Cent. III*, No. 298 (1898).
1912. *Ephydra hians* Say. J. M. Aldrich, "The Biology of Some Western Species of the Dipteron Genus Ephydra," *Jour. New York Ent. Soc.*, Vol. 20 (1912), pp. 77–99.
1917. *Chlamydomonas* sp. *Aphanothece packardii*, also two diatoms probably genera *Navicula* and *Cymbella*. L. L. Daines, "Notes on the Flora of Great Salt Lake," *Amer. Nat.*, Vol. 51 (1917), p. 499.
1917. *Artemia gracilis*, the larvae of *Ephydra gracilis*, amoeba of two or three varieties (most common similar to *Amoeba limax*), specimens of *Ciliata* (some closely resembling a species of *Uroleptus*), and a species of *Euglena* (seen once). Charles J. Vorhies, "Notes on the Fauna of Great Salt Lake," *Amer. Nat.*, Vol. 51 (1917), p. 494.
1918. *Artemia gracilis*. Albert C. Jensen, "Some Observations on *Artemia gracilis*, the Brine Shrimp of Great Salt Lake," *Biol. Bull.*, Vol. 34, No. 1 (1918), pp. 18–25.
1919. *Uroleptus packii*, *Prorodon utahensis*. "Two Ciliata of Great Salt Lake," *Biol. Bull.*, Vol. 36 (1919), p. 273.
1924. Eleven bacilli and one coccus. Elfreda Frederick, *The Bacterial Flora of Great Salt Lake*. Thesis submitted to the University of Utah (May, 1924) 65 pp.
1926. Three species of *Ephydra* larvae and pupae in their cases, one of the *Corixidae*, and *Artemia gracilis*. W. C. Allee, "Some Interesting Animal Communities of Northern Utah," *Scientific Monthly*, Vol. 23 (1926), pp. 481–95.
1934. *Aphanothece utahensis* Tilden, *Microcystis packardii* Farlow (Tilden), *Oscillatoria tenuis* var. *togestina* (Keutz) Rab., *Oscillatoria tenuis* var. *natans* (Keutz) Rab., *Chlamydomonas* sp., *Tetraspora lubrica* var. *lacunosa* Chauv. Seville Flowers, "Vegetation of the Great Salt Lake Region," *Bot. Gaz.*, Vol. 95, No. 3 (1934), pp. 353–418.
1936. 24 genera and 62 species of diatoms from lake bottom samples. Ruth Patrick, "Some Diatoms of Great Salt Lake," *Bull. Torrey Bot. Club*, Vol. 63 (1936), pp. 157–66.

From the foregoing list of species it is evident that the same form has often been observed by different authors and that different names have probably been given to the same species. This is true in particular of the algae. Kirkpatrick believes that 5 species of blue-green algae are present, all belonging to the genus *Aphanothece*. These have been variously assigned to *Microcystis*, *Polycystis*, and *Aphanothece*. Since the blue-green algae are very important as bioherm[28] builders in Great Salt Lake, samples of the algae from the extensive algal deposits were collected by the writer and submitted to W. R. Taylor of the University of Michigan, who in turn sent them to Francis Drouet of the University of Missouri for identification. Drouet's determinations are as follows.

East shore of Bird Island. Only *Aphanothece Packardii* (Farl.) Setch. were found to be present. A few more elongated cells might be referred to *Gloeothece* but these are so very few with intermediate conditions between this and the *Aphanothece* that it looks rather plausible that the cells are actually anomalous

[28] A term used to denote a calcareous deposit due to colonies of organisms. See Twenhofel, *Treatise on Sedimentation* (1932), p. 296.

forms of the *Aphanothece*. This entire material matches up so perfectly with Tilden's collections from Garfield Beach (locality L) that it is undoubtedly correct to assume the Bird Island algae to be *A. Packardii*. Miss Tilden collected Farlow's *Polycystis Packardii* and her type of *A. utahensis* both at the same place. I have examined her material of both and feel that Setchell is quite correct in considering the two synonymous.

Northeast shore of Stansbury Island (*locality Ac*). Same as above, east shore of Bird Island.

Northeast shore of Stansbury Island (*locality Ac*). These specimens differ from the common irregular and nodose deposits in having lamellar structure (description will be found in section of paper on algal deposits). I am sure that this is a *Pleurocapsa*, and nothing else seems to be present except some of the *Aphanothece Packardii*. Whether the form is actually new or not I have not been able to tell. It seems pretty close to *Pleurocapsa entophysaloides* Setch. and Gard., though the cells are somewhat smaller than in the typical material which I have not yet seen. I feel, however, that if it does not belong to this species it has not yet been described. For the time being it should be referred to as a form of *Pleurocapsa entophysaloides*.

Plankton in foam off Carrington Island (*locality Aa*). I find no blue-greens at all in this material. There are quite a few flagellates of some sort, either *Trachelomonas* or *Peridinium* or both, and some filamentous fungi. Many brine shrimp eggs are present.

Bottom samples of the clays from 24 localities were submitted to Ruth Patrick[29] of Temple University for diatom study. A summary of her findings is as follows.

1. 24 genera and 62 species were identified.
2. Diatoms are found in the bottom sediments chiefly in the Bear River Bay and Rozell Point regions. The Jordan River delta was not sampled but the conditions there are about the same as in and around Bear River Bay, thus implying the existence of diatoms in the Jordan delta region also.
3. The diatoms are all fresh- or brackish-water species except those at locality A where some questionable marine forms were found. It is thus concluded that they have not established themselves in the lake.
4. The distribution is accounted for by
   a. The existence of extensive fresh to brackish water sloughs in the Bear River Bay region where the diatoms live and multiply, with great numbers of wild aquatic fowl to distribute them
   b The probable existence in the very recent past of fresh and brackish swamps in the Rozell Point region
   c. The distributing power of the wind in carrying diatoms to random places in the lake. About 45 per cent of the material constituting the deep lake-bottom clays, as is shown on a subsequent page, is of wind-blown origin. Dust which commonly contains diatoms falls in Salt Lake City
   d. Creeks and rivers carry some fresh-water diatoms into the lake
5. Diatoms taken at 20 feet below the surface clays are chiefly fresh-water species, a fact which corresponds with the past fresh-water history and desiccation of the lake.

The Sediments

The sediments of Great Salt Lake may be divided into three major varieties which are quite distinct and suitable for mapping.

[29] Ruth Patrick, *op. cit.*, pp. 157–66.

They are the clays, the oölites, and the algal "bioherms."[30] All three are believed to have been derived from the same source materials but through varying mechanical influences or the activity of the plants or animals in the lake have acquired different physical characteristics and quantitatively different chemical compositions. Other kinds of sediments border the lake, such as alluvial fans and Lake Bonneville delta sands and bottom clays, but the present study has been purposely limited to the subaqueous deposits below the upper limit of the lake's recent fluctuations.

CLAYS

DISTRIBUTION

Fine-grained, plastic sediments, for the most part classified as clays according to the U. S. Bureau of Soils standard,[31] are widely distributed on the lake bottom. Figure 2 shows the approximate extent of the clays as well as the other types of sediments. The western part of the lake contains clay or clay loam covering the entire bottom below a depth of about 12 feet (lake level, August, 1933). In embayments protected from wave action, commonly in water shallower than 12 feet, clay to sandy clay loam exists which is difficult to distinguish megascopically from that of the deeper lake areas. Examples of such occurrences are the shore east of Rozell Point, the area around the southern end of Stansbury Island, and most of the shallower eastern part of the lake.

MEGASCOPIC DESCRIPTION

The clays range in color from black to light tan with shades of gray predominating. All the clays collected were plastic, some very sticky, smooth between the fingers, and easily deformed; others fairly firm and less sticky. It was found possible to thrust by hand a Musselman marl sampler down through 20 feet of the clay at Rozell Point and if a hard object had not been encountered a greater depth could have been obtained. In the building of the Lucin Cut-Off the deepest part of the lake was traversed with a trestle constructed by driving piles into the soft clay. According to maintenance engineer Weeks, of the Southern Pacific Railroad at Ogden, Utah, the outer

[30] The term "bioherm" has been appropriately introduced into geologic literature by Cumings and Shrock to signify any calcareous deposit due to colonies of organisms. *See* William H. Twenhofel, *Treatise on Sedimentation*, 2d ed. (1932), p. 296.

[31] The classification of the U. S. Bureau of Soils is preferred by the writer because it shows in the name describing the sample the size distribution, whereas Wentworth's scale indicates only the average size. See the following references.

H. H. Bennett and R. O. E. Davis, "Classification of Soils on the Basis of Mechanical Analysis," *U. S. Dept. Agric. Circ. 419* (1927).

Chester K. Wentworth, "A Scale of Grade and Class Terms for Clastic Sediments," *Jour. Geol.*, Vol. 30 (1922), pp. 377–92.

piles were driven down through 112 feet of clay and were still going at the rate of 1 inch to the blow when driving was discontinued. Even at the present, that part of the cut-off at Rambo is sinking at the rate of 2 inches per year. A still more notable example of the extreme plasticity of some of the clays is that of the building of the Bear River trestle, east of Promontory Point. Large blocks of stone unloaded from the quarry at Promontory Point settled into the clay bottom and disappeared out of sight. So much rock was dumped in before a surface above water could be maintained that, according to Weeks, if the rock had remained as a wall the width of the cut-off at the surface and did not disperse laterally as it sank, it would represent a dike 776 feet in depth. The clay of lighter density than the rock rose on either side of the fill to such a height that a passing train could not be seen from a boat on the lake. In the central part of the lake this highly plastic clay must have accumulated uninterrupted to a thickness of, at least, several hundred feet. A collector can not but be impressed with the property of sticky plasticity in most of the lake clays.

MECHANICAL ANALYSIS

Ten samples from widely separated but representative localities were mechanically separated into various fractions by M. W. Senstius, of the University of Michigan, and the writer, following the method of the U. S. Bureau of Soils. The results are contained in Table VIII. Because of a high percentage of chemically precipitated calcium and magnesium carbonate which is not part of the clastic content, it was found necessary to dissolve out the carbonate before making the analyses.[32] In all the determinations the contents smaller than 0.005 millimeter in diameter are considerable and the samples are accordingly described as clay, clay loam, or sandy clay loam. Certain near-shore samples such as M and Ai contain much sand and silt, a fact that was anticipated because of the nearness of Stansbury Island and Antelope Island, respectively, from which much clastic material must have been washed. Sample O is made up mostly of fine sand which comes probably from small shifting dunes along the west shore in that vicinity. However, it is not everywhere true that the near-shore sediments are coarser than the deep lake sediments. Samples Y, Z, and Aa, collected from the lake bottom at points farthest removed from shore, show less clay than a sample collected near shore at Rozell Point. This apparent anomaly is discussed on a subsequent page.

[32] About 5 per cent of the total sample is wind- or water-transported grains of calcite, which is removed by acid treatment. See Table IX.

TABLE VIII

MECHANICAL ANALYSES OF GREAT SALT LAKE CLAYS AND LOAMS[1]

Sample and Map Location	Coarse Sand 1–1/2 Mm.	Medium Sand 1/2–1/4 Mm.	Fine Sand 1/4–1/10 Mm.	Very Fine Sand 1/10–1/20 Mm.	Silt 1/20–1/200 Mm.	Clay <1/200	Sand Loss during Analysis	Carbonate Content	Classification	Description and Field
B				8.6	43.3	47.3	0.8	25.9	Clay	Blue-gray clay from craterlets of oil seeps. Sticky and smooth
F	1.6	1.5	9.4	22.7	45.2	19.1	0.5	ca. 40.0	Loam	Near shore under 3 inches of water
H	1.1	4.2	5.1	19.2	54.2	15.7	0.5	39.9	Loam	Light gray clay under 4 inches water near refuge dike
I	0.1	0.2	3.2	21.7	45.6	27.6	1.6	26.1	Clay loam	Drab gray clay taken 8 inches below surface under black ooze
M	1.3*	5.2	24.5	9.5	24.4	33.9	1.2	56.9	Clay	Tan-gray loam from dry lake bed
O	0.6	2.5	65.2	5.9	14.6	10.8	0.4	28.5	Sandy loam	Tan-gray clay 8 inches below surface under black mud. No water cover at present
T		3.8	8.4	32.1	25.7	30.0	0.0	ca. 70.0	Clay loam	Tan-gray clay under 9 feet water
Y				32.1	41.4	26.0	0.5	43.1	Clay loam	Light blue-gray clay from middle of lake under 30 feet water
Z and Aa	1.0	2.3	6.8	16.8	36.6	35.8	0.7	48.7	Clay	Light blue-gray clay from middle of lake under 14–30 feet water
Ah	2.5	1.7	23.9	43.5	21.1	7.0	0.3	?	Sandy loam	Tan-gray clay from lake bottom east of Dooley Ranch
Ac		11.4	3.7	8.6	39.8	35.0	1.5	None	Clay	Salt water foam containing dust dropped from air
Dust fall Salt Lake City	0.7	0.5	2.6	19.5	8.9	66.8	1.0	None	Clay	Dust fall on roof of Boston Bldg. 1918, Salt Lake City. Collected by J. C. Alter

[1] The carbonate content was first dissolved out with *HCl*, but is listed on the basis of the total sample. Analysis according to the U. S. Bureau of Soils method by M. W. Senstius and the writer. Carbonate analysis by K. A. Gorton.

* Also 1.0% sand > 1 mm. in size.

TABLE IX

Microscopic Determination of Physical Constituents in Great Salt Lake Sediments

The medium and fine sand fractions of the mechanical analyses (Table VIII) were separated into heavy and light divisions with bromoform, and permanent slides were made of the two parts. These were submitted to Professor W. F. Hunt of the Department of Mineralogy, University of Michigan. Those samples indicated by stars (*) are his determinations and are, perhaps, 80 per cent complete. The other determinations are by the writer and show only the major constituents present. The figures are percentage estimates by the writer. For further description of dust samples, see Tables VIII and XI. Sample *F* was taken from a dust catcher erected on Promontory Point; dust fall from July, 1934, to September, 1935.

Type of Sediment	SAMPLE		MINERAL AND ROCK GRAINS																												ADDITIONAL MATTER				
	Map Location	Sample Fraction	Apatite	Augite	Biotite	Calcite	Chert	Chlorite	Epidote	Felsite	Garnet	Glass	Glauconite	Hematite	Hornblende	Hypersthene	Ilmenite	Kaolin	Leucoxene	Magnetite	Microcline	Muscovite	Orthoclase	Plagioclase	Pyrite	Quartz	Rutile	Sericite	Schist, slate, and shale	Staurolite	Titanite	Tourmaline	Zircon	Oolites	Fæcal Pellets	Shrimp Eggs	Diatoms	Organic Matts
Clays and Loams	B	1/2–1/20 mm.			x	55		x							x								x	x		10						x		30		x	5
	D	Clay washed out			x				x																	x						x		98	x		
	G	Clay washed out		x	x	55		x							x			10					10	x		15						x	x			x	x	
	*H	1/4–1/20 mm.			x	x		x							x	x				x		x	x			x		x				x				x	
	*I	1/2–1/20 mm.			x			x	x					x	x						x		10			30			x				x	15	15	10		
	*J	Clay washed out		x	x	10		x							x			x					5	x		60							x		10	5		5
	M	1/2–1/20 mm.			x	20			x						x											5								50	20			
	*O	Clay washed out		x	x	40		x	x		x	x		x	x	x	x	x	x	x	x		20	5	5	20				x	x	x	x		x	x	x	
	P	Clay washed out							x														x	x		x									95			
	*T	1/4–1/20 mm.			x		x		x		x	x			x						x	x	x	x		x	x	x		x	x	x	x		x			
	*X, Y, Z & Aa	1/2–1/20 mm.			x		x	x	x			x		x	x							x	x	x		5	x	x			x				65	x	x	
	*Ai	1/4–1/20 mm.	x		x	x		x	x						x		x		x	x		x	x			x									60			
Oolites	*A	HCl residue	x	x	x				x	x		x		40	x			x	x			x	15	x		25			x			x	x		5		x	
	*F	HCl residue		x	x			x				x		5			x	x				x	10			40		x							40			
	K	HCl residue													x			x					30			40							x		20			
	N	HCl residue			x				x					x	x			5					30			20						x			20			
	R	HCl residue													x						x		10			50			20						10			
	*S	HCl residue			x			x	x		x				x		x	5	x	x			35		x	25		x	20						5			
Bio-herms	*B	HCl residue		x	x				x	x				x	x			5				x	25			45			10			x	s		5	x	x	
	Ac	HCl residue			x				x						x			5					30			60							x					
Dust	*Ac	1/4–1/20 mm.	x	x	x	x		x				x			x						x		x	x		x	x					x	x					
	*F	1/4–1/20 mm.	x		x	x		x				x		x	x	x				x		x		x		x	x				x	x	x					
	Salt Lake *City	1/10–1/20 mm.			x	x		x				x	x		x		x		x	x		x	x			x	x											

PETROGRAPHIC ANALYSIS

The sand fractions of the mechanical analyses were separated into heavy and light parts by bromoform of 2.7 specific gravity. Permanent slides of the heavy and light divisions were made and submitted to W. H. Hunt of the University of Michigan who has very kindly identified the minerals shown in Table IX. Altogether 30 minerals were recognized, and in addition, grains of felsite, schist, slate, shale, oölites, faecal pellets, and eggs of the brine shrimp, diatoms, and small masses of organic matter(?). As many as 23 minerals were found in one sample from locality O near Johnson's Ranch on the west side of the lake. The more durable detrital minerals had here already suffered concentration in sand dunes and when further concentrated by heavy liquids, a rich assortment of minerals appeared in the heavy mineral fraction. A greater variety of minerals was anticipated from the sediments around Antelope Island than anywhere else because of the various crystalline pre-Cambrian rocks that constitute the island. Twenty-five minerals were recognized from the sediments around the island but only seventeen in any one sample (T).

The clay and silt fractions of some of the typical plastic sediments were submitted to Albert B. Peck of the Department of Mineralogy, University of Michigan, who recognized a number of minerals in spite of the fine subdivision. The carbonate minerals he found are of two kinds, aragonite, and a dolomite having an index of 1.685. Such an index implies a ratio of *Mg* to *Ca* of about 2:1. Some of the very small carbonate grains in these clay fractions may have an index closer to 1.690 than 1.685 but the range of variation is small if present at all. No magnesite was found. Aragonite and dolomite were looked for in the sand fractions but were not found. Apparently the mechanical analysis had separated the coarser, clastic, calcite grains from the finer, chemically precipitated aragonite and dolomite crystals. Besides the two carbonate minerals, a whitish yellow constituent with index of about 1.52 to 1.53 was noted. This, if a single mineral, may be one of the group of bentonite minerals such as montmorillonite. The presence of a hydrous magnesium silicate, parasepiolite, as a part of, or in addition to, the whitish yellow constituent was suspected as a result of Rubey and Callaghan's work[33] on the magnesite deposits of the Boulder Dam region. Parasepiolite has an index within the range of variation of the index of montmorillonite; hence, it presents a difficult problem petrographically with these clays. The constitution of the fine clay fraction may be in-

[33] Eugene Callaghan and W. W. Rubey, "Mineral Resources of the Region around Boulder Dam," *U. S. Geol. Survey Bull. 871* (1936), pp. 106–38.

vestigated chemically. The results of such an investigation are described in the next section, "Chemical Analysis." The minerals identified in the fine clay have not been added to Hunt's determinations, Table IX.

CHEMICAL ANALYSIS

Table X lists 20 clay samples for which partial analyses were made. In view of the abundant plant and animal life in the lake chiefly in the form of algae, brine shrimps, larvae of the small fly, *Ephydra gracilis*, the abundant microscopic organisms, and the manner of accumulation of these forms along the shore there apparently to die and decay, it was anticipated that at least some of the clays would run much higher in organic matter than that actually found. The determination of the organic content has an added interest because of its possible relation to the origin of the oil seeps at Rozell Point. It was thought that the oil might have formed by reaction of the salt water with the organic matter in the clays. The analyses show the organic content to range from 0.45± per cent to 2.17± per cent which is not large but may be significant. A discussion of some of the specific localities follows under the heading "Color of Clays," page 1354.

The average moisture content of the clays collected under water is 39.0 per cent on a total-weight basis and 64.4 per cent on a dry-weight basis. Where the lake has receded, leaving the clays exposed to the air, considerable moisture has been lost but in most places the deposits within the bluff line, even though exposed, remain very moist or saturated with water. Samples taken under air average about 30 per cent water (total-weight basis). One sample taken 20 feet below the surface clays at Rozell Point contained 30 per cent water (total-weight basis) but at the surface in the same locality the clay contained 43 per cent. The physical constitution of both appeared similar. This suggests expulsion of water under the weight of overlying sediments. Along this same beach there is other evidence of compaction. A rough hexagonal pattern of markings inclosing areas 5–20 feet in either dimension was observed extending northwestward for several miles. The marks were 3–6 inches wide and, when stepped upon, let the foot and leg submerge almost as if the clay were liquid. The markings appeared like small fissure eruptions and indicated rising or upwelling of clay. The pattern existed both where the lake had receded and out under water as far as one could wade (½ mile). The writer interprets the phenomenon as one of compaction of the underlying clay with the expulsion of water along contraction joints. By probing with a marl sampler the fissures were found to extend at least 10 feet down and appear to have a uniform width. After lithifica-

TABLE X

PARTIAL CHEMICAL ANALYSES OF GREAT SALT LAKE CLAYS
Plus a calculation of the amount of aragonite and dolomite ($Ca:Mg = 1:2$)

Sample	Organic Matter Per Cent			Moisture		Calcium, Magnesium, and Carbon Dioxide							Description of Sample
Location	N_1	N_2	$\frac{N_1+N_2}{2}\times 14$	Total Weight Basis	Dry Clay Basis	CaO	MgO	CO_2	Aragonite	Dolomite $Ca:Mg = 1:2$	Excess CaO	Excess MgO	
B	.070	.065	.95			10.7	3.2	10.15	17.14	5.17	0.10	1.64	Craterlet clay from Rozell Pt. oil seeps. Blue-gray, very fine, smooth and sticky
B	.150	.160	2.17	43.8	70.0	3.0	4.2	2.91	4.82	1.58	None	3.72	Craterlet clay from Rozell Pt. oil seeps. Gray-green and not so plastic and sticky as above
B	.045	.055	.70			3.6	2.7						Black mud under oölites at Rozell Pt. Very sticky, fine and smooth
B				30.3	45.0	8.7	2.3						Blue-gray clay taken under 2 feet water and 20 feet mud. Near oil seep craterlets at Rozell Pt.
D				58.5	130.4	16.3	4.4						Tan clay collected ½ mile west of Colin in 12 feet water
G				24.5	32.3	8.7	3.5						Tan clay from east side of Promontory Range. No present water cover and somewhat dried
H	.040	.035	.52			20.0	2.0						Drab gray clay from lake bed near dike west of Perry. Collected 3 feet below surface clay
I	.130	.130	1.82	35.2	54.7	9.6	4.3						Dark surface muck from lake bed west of Syracuse. Taken from upper 2 inches. No water cover at present
J	.150	.155	2.13			11.9	5.1						Dark surface muck under salt pan west of Farmington. No water cover at present
J				29.9	42.7	11.6	6.3						Gray clay taken 12 inches below surface west of Farmington. Same locality as above
K	.035	.030	.45			14.9	8.9	18.91	21.25	14.80	None	*2.35	Gray-blue clay under oölites north of Saltair. Very smooth and sticky
M	.050	.060	.77	20.4	25.6	23.4	6.4						Tan-gray clay from lake bed SW. of Stansbury Island, ¼ mi. from R.R. track. No water cover at present
O				34.0	51.4	11.4	3.9						Tan-gray clay from lake bed east of Johnson's ranch. Taken 8 inches below surface clay. Water 2 mi. to E.
P				38.8	63.2	22.8	4.4						Tan clay collected one mile east of Rambo in 20 feet of water. Slightly coarse
Q				31.2	45.4	26.9	4.4	20.93	42.50	4.46	2.24	3.03	Tan-gray clay collected 4 mi. NW. of Saltair in 20 feet of water. Sulphur odor
T				40.8	68.8	16.9	6.9						Blue-gray clay taken in White Rock Bay under 8 feet water and 3 feet below surface (bottom) clay
T				21.6	27.2	37.3	3.5	26.33	55.90	3.46	5.32	2.45	Tan-gray clay taken at surface in 8 feet water. Same location as above
W				45.6	81.7	19.0	4.0						Tan-gray clay collected in middle of lake east of Carrington Is. under 25 feet water
X	.150	.150	2.10	51.2	90.8	18.2	5.1	14.48	26.78	5.40	2.14	3.46	Pale blue-gray clay collected in middle of lake E. of Carrington Is. under 30 feet water. Sulphur odor
Z				43.7	78.0	21.9	4.5						Tan-gray clay collected in middle of lake E. of Carrington Is. under 28 feet water

Organic matter, CaO, MgO, and CO_2 are figured on a moisture-free basis. The organic analyses are by H. E. Hammar, American Petroleum Institute while working with P. D. Trask. A nitrogen-organic content ratio of 14 is considered the best approximation. See Trask, *Source Sediments of Petroleum*, pp. 21–29. The CaO and MgO analyses are by K. A. Gorton of the Michigan Geological Survey. Each sample was treated with weak HCl and heated until reaction stopped. The CO_2 analyses were run by W. M. Spurgeon, a graduate student in the Department of Chemistry, University of Michigan. The above samples are all designated as clays although there is considerable variation from this type. See Table VIII.

* After the CaO had been satisfied in both aragonite and dolomite there remained an excess of 2.26 per cent CO_2, and 4.40 per cent MgO. The CO_2 was united with MgO as hypothetical magnesite, $MgCO_3$, leaving, still, an excess of 2.35 per cent MgO.

tion it is probable that sections through the resulting calcareous shale would show small dikes of mud rock, perhaps of a slightly different color, cutting across the shale beds. These would differ from filled mud cracks in not wedging out within several inches, in extending through 10 or more feet of strata, and in having thicknesses generally greater than mud cracks. The phenomenon near Promontory Point as seen from the air is shown in Plate 4a.

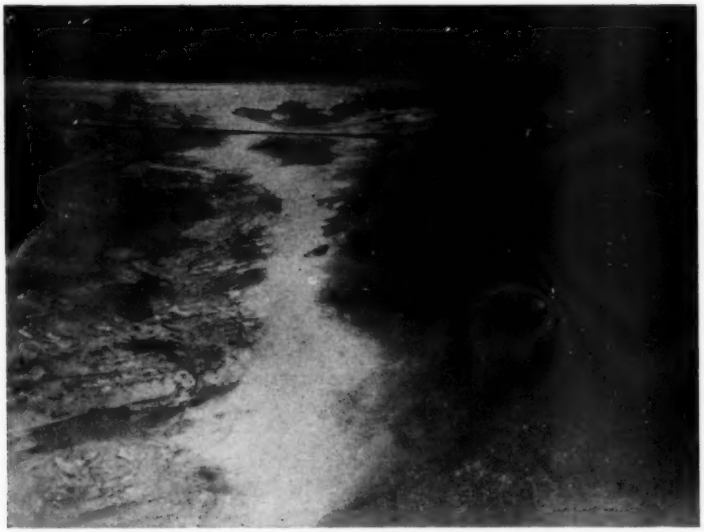
Another evidence of compaction is believed to be seen at Monument Rock where in the spring of 1934 an earthquake occurred. Monument Rock is an erosional outlier of Paleozoic sedimentary rocks almost surrounded by lake sediments. At the time of the earthquake several craterlets bordering the bedrock island came into existence. They flowed a cold concentrated brine. It is believed that the shocks caused considerable compaction of the soft hydrated clays around the island and the water thus eliminated came up along the bedrock contact.

The consistent presence of magnesium, compounds of which are soluble in weak *HCl*, is noteworthy. In some localities it is almost sufficient to render the clay, should lithification occur, an argillaceous dolomite. The average of such magnesium of the lake clays computed on the basis of *MgO* (Table X) is 4.5. The average soluble calcium content on the basis of *CaO* is 15.9. A maximum *CaO* content of 37.3 was found in a clay in White Rock Bay (T) on the west shore of Antelope Island. A maximum *MgO* content of 8.9 was found in a clay underlying the oölites just north of Saltair (K). The highest soluble *MgO*:*CaO* ratio was found in two clays at Rozell Point (B) where the average *MgO* content was 1.2 times as much as the *CaO*. No clay from any other locality yielded such a high *MgO*:*CaO* ratio. The presence of basalt cliffs at the water's edge is restricted to this locality and the ferromagnesian minerals of the basalts might have contributed the exceptional magnesium content. As noted earlier, this clay has less coarse clastic content than the deep lake clays. Other features of the carbonate content of the clays are discussed under "Origin."

Silica is undoubtedly also precipitated from true solution and colloidal suspension. Appreciable sodium and potassium are extracted from the lake waters as base ions associated with the colloidal clay particles. These subjects are treated at length under the next heading "Origin."

ORIGIN

Chemical precipitates.—All the clays have considerable calcium and magnesium carbonate content, whether near river mouths, near



PL. 4a.—Aerial photograph looking south-southeast from point just north of Colin on Lucin Cut-Off. Fringing algal bioherm is conspicuous in left foreground. White zone is oölitic sand with considerable fragmental bioherm material.

b.—Exposed lake bottom clays with pressure ridges in thin salt crust. Near Monument Rock, locality Ah, Fig. 2.

desert shores, or in the deepest part of the lake farthest removed from land. In the discussion of the chemistry of the lake water it was pointed out that the fresh-water streams, containing chiefly calcium and magnesium carbonate, empty into a carbonate-saturated lake water and, although diluting the lake water for a time, result in the precipitation of calcium and magnesium carbonate, when evaporation again concentrates the solution. The interval of time between dilution and evaporation permits thorough mixing of the river waters with those of the lake so that carbonate precipitation is widespread. Clarke[34] and Talmage[35] have observed the precipitation of calcium carbonate from the lake waters in the form of the oölites, Talmage also suspecting the presence of "a marly deposit in the deeper parts." The clays are more plentiful than the oölites and amply attest carbonate precipitation.

Although the physico-chemical process of calcium carbonate precipitation in Great Salt Lake seems adequate in itself to account for the large carbonate content of the lake-bottom clays, the lake bacteria must also play an important rôle. Bavendamm's[36] account of the "Kalkschlamm" of the Bahama Islands suggests the necessity of micro-organic research on the clays of Great Salt Lake. The strong emanations of H_2S from all the lake clays sampled betrays the presence of abundant sulphur bacteria. It is probable that other bacteria groups are present also, such as cellulose bacteria and denitrifying bacteria. Bavendamm[37] concludes that enough bacteria are present in the bottom sediments of sheltered lagoons, bays, and banks in the tropical seas to account for all the carbonate precipitation that has occurred there. Although the denitrifying and desulphatizing bacteria result in the liberation of CO_2 which is prejudicial to carbonate precipitation, other bacteria groups extract the CO_2 thus liberated, and by such coöperative activity carbonate precipitation results. The micro-organic content of the lake clays is discussed further under "Diagenesis."

In examining the chemical analyses of calcium and magnesium carbonate, either CaO or MgO or both are in excess of the combining ratio of CO_2 and hence in part must be combined or in colloidal association with other constituents. The petrographic examinations

[34] F. W. Clarke, "Data of Geochemistry," *U. S. Geol. Survey Bull. 770* (1924), p. 159.

[35] J. E. Talmage, *The Great Salt Lake, Past and Present* (1900), pp. 65–66. Published by Deseret Book Store, Salt Lake City.

[36] W. Bavendamm, "Die mikrobiologische Kälkfallung in der tropischen See," *Archiv für Mikrobiologie*, Vol. 3 (1931), pp. 266–69.

[37] *Ibid.*

have already shown that the principal carbonates present of chemically precipitated origin are aragonite, $CaCO_3$, and dolomite, $CaCO_3 \cdot 2MgCO_3$. Before attempting to calculate the proportion of aragonite and dolomite from the CaO, MgO, and CO_2 analyses of Table X, it is desirable to examine chemically the fine white material, because in so doing additional factors governing the assignment into various combinations of the oxides are brought to light.

TABLE XI

CHEMICAL ANALYSIS OF FINE WHITE MATERIAL IN CLAYS

Constituent	*Locality I*	*Locality Q and Z*	*Locality U*
SiO_2	44.26	30.78	45.58
Al_2O_3 (includes TiO_2 and Mn_3O_4)	10.10	6.06	8.02
Fe_2O_3 (total iron)	3.94	2.50	1.65
MgO	6.80	8.91	7.36
CaO	14.34	23.35	15.07
Na_2O	4.95	7.00	5.47
K_2O	3.61	2.93	2.07
P_2O_5	0.26	0.23	0.21
CO_2	11.59	18.61	14.31
H_2O (determined only for U)	?	?	0.70
Total	99.85	100.07	100.45

Each sample was separated from the coarser material by decanting, and then washed with distilled H_2O until $AgNO_3$ gave no further test for Cl. This was necessary to remove $NaCl$. The washed samples were then dried at 120°C. before analysis. Analyses by J. B. Schroyer, Department of Chemistry, University of Michigan.

Table XI gives complete analyses of the fine white material from three localities. In calculating the chemical analyses in terms of minerals present, the following petrographic observations must be satisfied.

The feldspar grains are chiefly orthoclase and albite. Quartz grains are about as common as feldspar grains. The clay minerals are about as common as the quartz and feldspar together. Aragonite is three or four times as common as dolomite.

The approximate composition of the clay minerals was determined as follows. When the carbonates are dissolved in HCl a fine flocculent material remains. Rubey called the writer's attention to the apparent similarity of this material with a silica gel obtained by digesting samples of Overton magnesite with acid.[38] The silica gel is believed to result from the breaking down of a hydrous magnesium silicate, probably parasepiolite, $2MgO \cdot 3SiO_2 \cdot 4H_2O$. The magnesium goes into solution with the calcium and magnesium of the carbonates. Callaghan and Rubey were unable to isolate the mineral for definite

[38] Eugene Callaghan and W. W. Rubey, "Mineral Resources around Boulder Dam," *U. S. Geol. Survey Bull. 871* (1936), pp. 130–33.

identification. Although Peck was able to determine the index of one clay mineral and two carbonates in a very fine state of subdivision in the Great Salt Lake clays, he likewise found that the carbonates effectively conceal the parasepiolite, if present. In an acid-treated sample only the clay mineral could be discerned. A suggestion of a colloidal material was noted, however, in the petrographic examination of an *HCl* residue from the concentric bands in the oölites. An extremely fine crystalline substance was found with an index of 1.54. Although too fine for Peck to determine definitely, the index suggests quartz. The evidence of a hydrous magnesium silicate is by no means definite but suggestive enough to warrant inclusion of it in the calculated list of minerals.

The mineral withindex 1.52 (p. 1338) can not be parasepiolite (index 1.50) because it has not broken down in acid treatment and must contain aluminum. In fact, a considerable amount of some aluminum silicate must be present in order to account for the excess Al_2O_3 more than the amount necessary to form the required 10–20 per cent feldspar. Peck believes the mineral is one of the bentonite group, possibly montmorillonite.

On the basis of the foregoing petrographic and chemical requirements, the mineral composition shown in Table XII was calculated. The amount of parasepiolite (?) was arbitrarily kept approximately constant in the three samples. The excess oxides, CaO, MgO, Na_2O, and K_2O are undoubtedly colloidally absorbed as base ions in and around the various kinds of colloidal particles. The principal mineral to attract these bases would be montmorillonite (?). The best conception of the colloidal clay in Great Salt Lake, according to Senstius,[39] is that of a "colloidal clay complex" in which the questionable parasepiolite and montmorillonite together with variable and in some places appreciable (5–13 per cent) absorbed bases are very complexly related. Any inquiry into the physical and chemical divisions of this clay complex must await the work of the colloidal chemist. The writer has taken the liberty to calculate the chemical composition in terms of definite minerals, parasepiolite and montmorillonite, in order to demonstrate that they are possible constituents and that they fit in nicely with the known facts.

Colloidal sediments in the environment of Great Salt Lake water might be expected to absorb preferentially Ca^{++} to Mg^{++}, or Na^{+} to K^{+}. From Table XII any such relations are not clear because the per cent of MgO, taken arbitrarily to unite with SiO_2 to form parasepiolite, may be considerably incorrect. Slight possible shifting of

[39] Oral communication, University of Michigan.

TABLE XII

CALCULATED MINERAL CONTENT OF FINE WHITE MATERIAL IN CLAYS

Mineral		*Proportion of Oxides Per Cent*	*Locality I Per Cent Total Sample*	*Locality Q and Z Per Cent Total Sample*	*Locality U Per Cent Total Sample*
Aragonite		CO_2 44.0 CaO 56.0	8.59 10.93 } 19.52	15.61 19.86 } 35.47	9.43 12.00 } 21.43
Dolomite ($Ca:Mg = 1:2$)		CO_2 49.9 CaO 19.6 MgO 30.4	3.00 1.18 1.82 } 6.00	3.00 1.18 1.82 } 6.00	4.88 1.83 2.97 } 9.68
Colloidal clay complex	Parasepiolite (?)	MgO 30.8 SiO_2 69.2	2.53 5.70 } 8.23	2.83 6.35 } 9.18	3.00 6.74 } 9.74
	Montmorillonite (?)	SiO_2 66.3 Al_2O_3 22.1 CaO 1.9 MgO 5.8 Fe_2O_3 3.9	18.36 6.11 0.53 1.61 1.08 } 27.69	11.12 3.70 0.32 0.98 0.66 } 16.78	14.83 4.90 0.42 1.29 0.87 } 22.31
Orthoclase and albite (1:1)		SiO_2 66.7 Al_2O_3 19.0 K_2O 8.4 Na_2O 5.9	11.34 3.23 1.43 1.00 } 17.00	6.81 1.94 0.86 0.60 } 10.21	9.00 2.57 1.13 0.81 } 13.51
Green hornblende, glass, sericite, and various dark grains		SiO_2 43.0 Al_2O_3 12.0 Fe_2O_3 17.0 MgO 1.5 CaO 12.0 Na_2O 2.7 K_2O 1.0	2.51 0.70 0.99 0.09 0.70 0.16 0.06 } 5.21	1.50 0.42 0.60 0.05 0.42 0.10 0.03 } 3.12	1.99 0.55 0.78 0.06 0.55 0.12 0.05 } 4.10
Quartz		SiO_2 100.0	6.35	5.00	13.02
Hematite (?) and magnetite (?)		Fe_2O_3 100.0	1.87	1.24	None?
Apatite		P_2O_5 42.3 CaO 55.5 F(?) 3.8	0.26 0.34 0.03 } 0.63	0.23 0.30 0.02 } 0.55	0.21 0.27 0.02 } 0.50
Absorbed bases (Excess oxides)		CaO MgO Na_2O K_2O	0.66 0.75 3.79 2.12 } 7.32	1.27 3.23 6.30 2.04 } 12.84	None(?) 0.04 4.54 0.89 } 5.47
	Total		99.82	100.37	99.76

All oxides figured on a water-free basis to correspond with the analyses, Table XI. The composition of montmorillonite is that of an average sample. See C. S. Ross and E. V. Shannon, "Minerals of Bentonite etc.," *Jour. Amer. Cer. Soc.*, Vol. 9, No. 2 (1926).

other mineral amounts or changes in assumed composition of the minerals would alter the amount of excess bases. The writer suspected, however, the greater degree of absorption of Mg^{++} than Ca^{++} and prepared Table XIII which seems to confirm the belief. The

TABLE XIII

RELATION OF MAGNESIUM TO INSOLUBLES

Sample Locality	*CaO*	*MgO*	*Ratio CaO : MgO*	*Insolubles*
B	3.0	4.2	0.71:1	89.90
B	10.7	3.2	3.3 :1	75.95
X	18.2	5.1	3.6 :1	62.22
Q	26.9	4.4	6.1 :1	47.77
T	37.3	3.5	10.7 :1	32.87

Sample K is exceptional and is not included. The insolubles are figured on the basis of CO_2 content.

greater the percentage of insolubles, if colloidal, the greater percentage of Mg^{++} should be absorbed. That this is a definite tendency is shown by the fact that the *Mg*:*Ca* ratio is greater with more insolubles. However, if the magnesium were present as parasepiolite in a rather constant amount and not as an absorbed base, the relation would be about the same. The exact association of magnesium can not be solved at this time.

The analyses of Table X are of complete samples. On the basis of the distribution of *CaO* in aragonite and dolomite in the fractional samples of the fine white material, Table XII, a similar proportion was arbitrarily used in the calculations of the complete samples. This ratio (90 per cent *CaO* for aragonite, 10 per cent for dolomite) proved quite satisfactory. In half the samples the *CaO* was combined completely, leaving no excess, whereas in the other half 2.14–5.32 per cent remained in excess. *MgO* excess ranged from 1.64 to 3.46 per cent and is more constant than *CaO*.

Part of the $CaCO_3$ calculated as aragonite is calcite. The mineral determinations of Table IX show an average of 15 per cent of the sand fractions to be calcite grains. The sand fractions constitute one-third by weight of the total sample. Therefore, the calcite grains make up about 5 per cent of the bottom-clay material of the lake. This amount must be subtracted, on the average, from the amount of aragonite in Table X in order to obtain a true percentage of the amount of aragonite precipitated chemically.

The origin of the silica of the colloidal clay complex is a problem of interest. The silica could have been carried into the lake by the rivers either in true solution or in colloidal form. Shore processes might have mechanically broken down the quartz particles to colloidal dimensions. The wind might have transported quartz grains of such fine size that they acted as colloidal particles after falling into the brine. Again, all these processes may have contributed in part to the silica of the clay complex.

The mechanical processes of rock comminution such as the activity of wind and waves are not believed to be very effective in reducing quartz particles to colloidal size. According to Senstius[40] quartz can be ground with difficulty to colloidal size in the laboratory, and it has been found that quartz particles of the size ordinarily carried by the wind do not exhibit colloidal properties. Silica in colloidal subdivision is ordinarily due to chemical weathering of silicate minerals, namely, hydrolysis of feldspar and various ferromagnesian silicate minerals.

If a hydrous magnesium silicate is present, its silica content must have been derived from silica in true solution or in colloidal suspension. Silica in such condition probably was carried into the lake by the tributary rivers. The silica in a bentonitic mineral like montmorillonite is undoubtedly the result of chemical weathering. However, the montmorillonite may have entered the lake as such in colloidal suspension, and not have been formed by chemical reaction within the lake waters or as a diagenic product from silica gel and other constituents in the lake waters. Analyses of the tributary waters are too incomplete to afford a definite solution to this problem. Bear River, alone of the major tributaries, has been reported carrying SiO_2 and Al_2O_3 in solution. Most probably colloidal silica would be included in the analyses. At Evanston 3.84 per cent SiO_2 is reported (Table IV) in water having a salinity of 185 parts per million, and at Corrine, near its mouth, 2.53 per cent $(Al, Fe)_2O_3$ in water having a salinity of 637 parts per million. SiO_2 is not given in one analysis and Al_2O_3 not in the other. It appears that SiO_2, Al_2O_3, and Fe_2O_3 were all precipitated together and called SiO_2 in one analysis and $(Al, Fe)_2O_3$ in another. This is supported by the fact that the percentages add up to 100 per cent in each analysis. Assuming SiO_2, Al_2O_3, and Fe_2O_3 to be contained in each sample to the amounts indicated after "SiO_2" and "$(Al, Fe)_2O_3$," the Evanston sample contained 4.6 per cent as much silica, alumina, and iron oxide as calcium and magnesium carbonates, and the Corrine sample contained 6.8 per cent as much. How representative the average figure, 5.7[41] per cent, is for the other tributary rivers is not known.

A comparison of chemically or colloidally precipitated carbonates and silicates in the lake with those in the water of Bear River may approximately be made. According to Table XII the montmorillonite (?) and the SiO_2 of the parasepiolite (?) amount to 26.8 per cent of

[40] M. W. Senstius, soil geologist, University of Michigan.

[41] It was thought best to average the two analyses because they were taken at different times, and not to use the lower river one (Corrine) solely.

the fine white material. As the fine white material constitutes the clay and part of the silt fractions from Table VIII, it makes up about 50 per cent of the lake clays. Montmorillonite and the silica of the parasepiolite, therefore, compose about 13 per cent of the entire lake bottom clays. The average total carbonate plus absorbed Ca^{++} and Mg^{++} is about 35 per cent in the clays. The percentage ratio, 13.5/35 = 38 per cent, for the lake clays is much more than 5.7 per cent for the Bear River water. However, the widespread areas of oölitic sand and bioherms with their much higher carbonate content will lower the proportion of silicates to carbonates appreciably, and make probable the conclusion that the streams tributary to the lake are carrying in solution and suspension about 5.7 per cent SiO_2, Al_2O_3, and Fe_2O_3 and 35 per cent Ca, MgO, and CO_2, and that these are being chemically precipitated in the lake in about the same proportion, considering all types of sediments.

Sand, silt, and clay fractions.—In addition to chemically precipitated calcium and magnesium carbonate and the colloidal clay complex, the other chief constituent of the clay is clastic material. The sand and about 50 per cent of the silt fractions of the mechanical analyses are composed of mineral particles and faecal pellets of the brine shrimp, but here and there oölites are found. Where oölites were found in the clay the sample was collected either on the margin of the oölite zone (Fig. 2) or on exposed stretches of the lake bottom over which the wind has drifted some oölitic sand. It is believed that the oölites and faecal pellets (pp. 1359 and 1401) result from the activity of special physical processes or animal life using the clays as source material. The sand and silt fractions, composed of mineral fragments, must have been deposited by the lake water, but either wind or water currents could have transported the grains to the site of deposition.

It is generally believed that offshore currents (undertow) or longshore currents decrease in effectiveness with depth in transporting clastic particles. Great Salt Lake clays in shallow embayments might logically be accounted for, at least in large part, by lake current transportation, but the deep-lake clays may lie below the lower limit of water movement, which from the study of the oölites, is about 12 feet. The deep-lake samples X, Y, Z, and Aa were collected under 20–30 feet of water and 6 miles from the nearest landmass from which sediments could be derived. The gradient of the bottom from Antelope Island to locality Y is 5 feet per mile. Under these conditions it might seem improbable that any but the finest clay particles have been transported by lake currents to the central and deep part of the lake.

Eakin's[42] study on the silting of reservoirs, however, shows that clay and silt particles are carried in large amounts to depths below 100 feet in bodies of water somewhat comparable in size to Great Salt Lake. For instance, about 65 per cent of the sediments brought into the San Carlos Reservoir, Arizona, by the tributary streams have accumulated at depths ranging from 50 to 200 feet. Circulation in the waters of Great Salt Lake is sufficient to carry the carbonates of the river waters in solution to all parts of the lake and also may be sufficient to transport much fine material in suspension to the deep-water areas. Another conflicting thought is the flocculating power versus the suspending power of the heavy brine. Without direct observation of the transporting power of the lake waters, such speculation as the foregoing leads to no reliable conclusion. The problem may be approached from another angle, however. If the proportion of soluble material to suspended material that the tributary rivers bring into the lake is known and the distribution of chemical precipitates in relation to mechanical (clastic) contents is determined, an estimate of the amount of material carried out from shore by lake currents may be ascertained.

The approximate average per cent of chemically precipitated sediment for the three types of Great Salt Lake clays is as follows. (This includes aragonite, dolomite, parasepiolite (?), and absorbed bases.)

	Per Cent
River-mouth sediments in eastern division of lake	33
Deep-lake sediments in western division of lake	47
Near-shore sediments in western division	29
Average, equally weighted	36

According to Dole and Stabler[43] the solids carried by the streams of the Great Basin (presumably a measurement on the Bear River) are 64 per cent dissolved and 36 per cent suspended. If the average sediment precipitated from solution in Great Salt Lake is 36 per cent of the total sediment, 20 per cent of the sediment must be water transported and deposited. The proportion is as follows.

$$\frac{36}{x} = \frac{64}{36} \qquad x = 20 \text{ per cent.}$$

The average origin of the Great Salt Lake clays would then be

	Per Cent
Transported by lake currents	20
Transported by wind	44
Precipitated from solution	36

[42] H. M. Eakin, "Silting of Reservoirs," *U. S. Dept. Agri. Tech. Bull. 524* (1936), pp. 90–91.

[43] R. B. Dole and H. Stabler, "Denudation," *U. S. Water-Supply Paper 234* (1909), p. 84.

Material in colloidal suspension is included in the first item, "Transported by lake currents."

Examination of wind-blown dust in the Great Salt Lake region and its comparison with the sand, silt, and clay fractions of the lake clays confirm the calculations which show the air currents to be a very active agent in transporting the coarser clastic part of the clays to the various parts of the lake.

TABLE XIV

GRAIN SIZE COMPARISON OF LOESS WITH GREAT SALT LAKE CLAY AND DUST

	Coarse Sand 1.0–0.5 Mm. Per Cent	*Medium Sand 0.5–0.25 Mm. Per Cent*	*Fine Sand 0.25–0.10 Mm. Per Cent*	*Very Fine Sand 0.10–0.05 Mm. Per Cent*	*Silt 0.05–0.005 Mm. Per Cent*	*Clay 0.005–0.00 Mm. Per Cent*
1. Loess from Nebraska	0.2	0.4	1.7	26.7	50.7	11.3
2. Loess from Illinois	0.5	1.03	0.76	7.07	69.76	19.98
3. Average Y, Z, and Aa deep lake samples, Great Salt Lake	0.5	1.15	3.4	24.5	39.0	30.9
4. Dust on foam, Ac, Great Salt Lake		11.4	3.7	8.6	39.8	35.0
5. Dust Fall, Boston Bldg., Salt Lake City, 1918	0.7	0.5	2.6	19.5	8.9	66.8

1. Mechanical analyses of loess from Nebraska, by F. J. Alway and C. O. Rost, "The Loess Soils of the Nebraska Portion of the Transition Zone," *Soil Science* (Rutgers College), Vol. 1, No. 5 (1916), p. 407. Average of 36 samples.

2. Average of 7 "Upland loess" samples, 3 pervious and 4 poorly pervious. Frank Leverett, "The Illinois Glacial Lobe," *U. S. Geol. Survey Mon. 38* (1899), pp. 159–63. Percentages have been recalculated on a dry-weight basis to conform to other figures.

3, 4, and 5. See mechanical analyses, Table VIII.

The mineralogical composition of loesses varies widely but generally the most common mineral is quartz, with orthoclase, plagioclase, hornblende, biotite, tourmaline, carbonate, and clay colored with iron oxide ordinarily present.[44] Table IX shows nearly the same minerals quantitatively in the clays of Great Salt Lake. A few additional minerals were detected in the lake clays such as augite, epidote, chlorite, pyrite, apatite, leucoxene, zircon, and glass, all in very small amounts and apparently reflective of exposed rocks in the surrounding region. These minerals are noted in some loesses. Although loess grains and those of the lake clays are angular this can not be assumed to be a characteristic of wind-transported material because almost all very small clastic grains of whatever origin are angular.

The mechanical analyses lend equal support to the eolian theory. Loess analyses vary considerably, especially if much alteration has occurred since deposition. It is difficult to know if the sampled loess is greatly altered but in Leverett's "Upland loesses," perhaps a somewhat close approximation to the original nature is obtained (Table XIV). Loesses vary in grain size from one locality to another, namely, the Nebraskan loesses are coarser than the Illinoian loesses. The largest discrepancy between the Mississippi Valley loesses and the Great

[44] W. H. Twenhofel, *op. cit.*, p. 274.

Salt Lake clays is in the clay fraction which in the lake samples is greater by 10.9 per cent than that in the Illinoian loess average and 19.6 per cent greater than in the Nebraskan. The difference in clay-fraction content becomes less conspicuous when some actual dust-fall samples in the Great Salt Lake area are examined. Mechanical analyses of the dust samples are included in Table XIV. Dust that had settled directly on foam on the lake has a clay content of 5 per cent greater than that of the deep-lake clay, and dust that fell on the roof of the Boston Building in Salt Lake City had 30 per cent more clay. The mineral composition of the dust and lake clays is very similar (Table IX).

The relative activity of the air and water currents in transporting the clastic material to the river-mouth areas of the eastern lake division and the deep and the near-shore areas of the western division is a problem that can be still less accurately solved. If the dust fall is uniform over the lake the problem resolves itself into an equation of two known variables (water current transportation and chemical precipitation) and one constant (wind transportation), and is easily figured. Undoubtedly more coarse material is dropped in the lake along the shores by the wind than in the central parts of the lake, and the more arid climate of the western division is more conducive to dust storms than the eastern division. No relative dust-fall data are available. In order not to leave the problem without an approximate solution, the following arbitrary relative dust falls are assumed, allowing first, the area of maximum fall to equal 100 per cent, and then, multiplying each by a factor sufficient to make them average 100 per cent.[45]

	Per Cent	*Per Cent*
Near-shore areas of western division	100	(127)
Mid-lake areas of western division	75	(96)
River-mouth areas of eastern division	60	(77)

On this basis the chief constituents of the three areas of clay deposits originate as follows.

	Per Cent
1. River-mouth deposits in eastern division	
Clastic and colloidal material transported by lake currents	33
Clastic material (possibly some colloidal) transported by the wind and deposited in water	34
Precipitated from solution	33
2. Deep-lake deposits of western area	
Clastic and colloidal material transported by lake currents	11
Clastic material transported by wind and deposited in water	42
Precipitated from solution	47
3. Near-shore deposits of western area	
Clastic and colloidal material transported by lake currents	15
Clastic material transported by wind and deposited in water	56
Precipitated from solution	29

[45] The constant in the equation, therefore, becomes a known variable, also.

Montmorillonite (?) is considered in the foregoing tabulation to have been transported in colloidal suspension by the streams and lake currents, but parasepiolite (?) to have been precipitated out of true solution.

DIAGENESIS

Calcium:magnesium relationship.—The magnesium carbonate content of limestones and dolomites has often been considered of secondary origin with the inference, perhaps, that no dolomite was precipitated in the original deposit. The dolomite crystals of the Great Salt Lake clays are undoubtedly primary, a phase-rule relationship between the precipitates, aragonite, dolomite, and parasepiolite (?), apparently existing. Is magnesium in any way, however, being preferentially retained or taken out of solution?

The $CaO:MgO$ ratio of the clays on the basis of 20 analyses (Table X) is 3.3:1. This calcium and magnesium has been extracted with weak, hot HCl, and includes an appreciable amount from the colloidal clay complex. All of it, however, has been precipitated from solution in the lake waters. The ratio of $CaO:MgO$ in the fresh-water streams entering the lake is about 2.6:1, a figure arrived at by weighting the calcium and magnesium analyses of Table IV according to the respective stream discharges[46] and computing them on the basis of their oxides. Neither the chemical analyses nor the stream discharge data available are very satisfactory and the ratio is, therefore, approximate.

The ratio in the oölites (p. 1371) is $CaO:MgO=26:1$. The ratio in the algal deposits (p. 1398) is $CaO:MgO=11:1$. The three ratios, weighted approximately on the basis of the areal distribution of each type of sediment, is $CaO:MgO=8.6:1$. This composite ratio shows the MgO content of the river waters to be 2.8 times as much as in the lake sediments. Great Salt Lake waters have become greatly enriched in magnesium, containing at present 2.76 per cent magnesium and only 0.16 per cent calcium of the solid contents in solution. The lake reached its present high salinity at least 1,000 years ago and it is not probable that the process of magnesium concentration is continuing at present, particularly not, if dolomite crystals are being precipitated. The most plausible explanation of the greater magnesium content in the rivers than in the lake sediments is obtained from the concept of base exchange. The analyses of Table X show about 4.6 per cent of the total sample to be colloidally absorbed Ca^{++} and Mg^{++} ions. Generally, more magnesium is absorbed than calcium. In addition sodium and potassium are absorbed in large amounts (Table

[46] Data of stream discharge were taken from *U. S. Geol. Survey Water-Supply Papers 517* and *750*. (See Table I.)

XII), possibly five or six times as much as calcium and magnesium. If the weak *HCl*, in which the sediments were heated until reaction ceased, did not remove all of the absorbed bases, the discrepancy between the magnesium content of the river waters and the lake sediments is, at least partly, explained. A sample of oölites that was digested in *HCl* and washed free of the soluble material before analysis (Table XIII) contained about 21 per cent excess oxides of calcium, magnesium, sodium, and potassium. This appears to indicate that acid treatment and washing until free of Cl^- ions only removes part of the colloidally absorbed bases.

If sodium and potassium are also being absorbed in the lake sediments it is possible under existing conditions that potassium may never become more concentrated in the waters than at present, and that it will continue to be extracted from the water for some time in the future by the process of base-ion absorption at about the rate of entry into the lake. A suggested conclusion follows: in order that potassium salts form in an evaporite basin, the waters of which have the approximate composition of Great Salt Lake, desiccation must be very rapid or clay particles must be very limited.

Color of clays.—The activity of bacteria and other microscopic organisms should be investigated with reference to changes in carbonate and organic content in the clays and in relation to the color of the sediments. The lake-bottom clay flora is now being studied by ZoBell[47] and associates and as already noted their counts show the clays to contain from a few hundred to several hundred thousand viable bacteria per wet gram. Undoubtedly a certain group of these bacteria has caused the formation of the hydrogen sulphide gas that is so prevalent around the shores of Great Salt Lake and in bottom samples dredged from all depths. Some small botryoidal clusters of pyrite were observed in sample O, and may be the result of bacterial action. In view of the present lack of knowledge of the microscopic life in the lake clays it is necessary to await further study by the limnologist and bacteriologist before hazarding conclusions on problems of the sediments involving biochemistry.

Black clays have been noted at the following places: the east shore of the lake from the mouth of Weber River south through the Syracuse and Farmington sections almost to Saltair; the west shore of the lake north and south of Johnson's Ranch inland from the oölite zone; Rozell Point; and the southeastern shore of Promontory Point. The first and second localities are by far the most extensive and have a similar bipartite profile which could be easily studied in the summer

[47] Personal communication, Scripps Institution of Oceanography.

of 1933 with the lake level so low as to leave wide stretches of these areas above water. The upper layer consists of a black clay almost of oozy character which emits fetid and almost suffocating odors of hydrogen sulphide, apparently indicating bacterial decomposition of certain organic material embedded in it. This layer is 1–6 inches in thickness. At Syracuse (locality I) the organic content is 1.82± per cent and at Farmington (locality J) it is 2.13± per cent. On drying and powdering preparatory to analysis the black sample turned gray-white but it is not believed that much organic matter was lost in the process. At Johnson's Ranch (locality O) the black layer is about 8 inches thick and is overlain by a ½-inch layer of oölites. The black clay is underlain in both localities by a dull gray-green clay of undetermined thickness. The organic matter in the underlying clay is decidedly less than that of the black clay. A sample collected 3 feet below the surface at Perry (locality H) ran only 0.52± per cent. Other clays of similar appearance, as the table shows, also contain very little organic matter.

The origin of the black upper layer seemed quite evident in the field. It has the same sulphurous odor that the calcareous algal deposits exhibit (see section on "Algal bioherms," page 1392), and it was thought algae must be decaying in the surface clays, producing both the odor and the black color. The writer had observed somewhat extensive accumulations of algae, probably *Aphanothece Packardii*, drifted upon the shore and other travelers had reported them 6–12 inches deep and covering acres. Talmage[48] says that the pupa cases of the tipula larvae "are often washed ashore in great numbers, where they undergo decomposition with disagreeable emanations." It was also considered in the field that these pupa cases may be in the clay along shore. However, when the samples were microscopically observed in the laboratory neither algae nor pupa cases were found upon cursory examination but, surprisingly, a new form—abundant small semi-spherical chitinous-like objects about 0.15–0.2 millimeter in diameter. These proved to be the eggs of *Artemia gracilis*, the brine shrimp. On further examination they were found in the deep-lake sediments and also floating in several water samples taken from different parts of the lake. During the following summer (1934) many were observed. The discovery of these abundant forms indicates that the organic content of the clays may be due not only to one or two life forms, but to many others not yet described or identified. Speculations on the origin of color and related organic problems such as petroleum generation in the clays seem premature until systematic

[48] J. E. Talmage, *The Great Salt Lake, Past and Present*, p. 68.

study has been made of the life content by the limnologist and bacteriologist, but some of the data, presented here, may be of aid to investigators of the life of the lake which appears to be an inviting study.

The black color is not in all places a result of the presence of organic matter. A black clay which is found locally at Rozell Point is low in organic matter (0.70± per cent) while a tan-gray clay collected in 25 feet of water east of Carrington Island in the middle of the lake (locality X) contains 2.10± per cent or as much as the black clays along the east shore. The black clay at Rozell Point undoubtedly owes its color to dark minerals from basalt cliffs along the shore. The deep-water clay has decided sulphurous odors and probably supports a rich bacterial flora.

"Red beds" have often been associated with desert conditions and salt deposits. An interesting commentary that arises from the study of the sediments of Great Salt Lake is that no red sediments of any description occur. There are black, blue-gray, gray, gray-green, and tan-gray colors but no limonite or hematite reds. Some chemically precipitated iron must surely exist in the lake sediments because of the ferromagnesian minerals of the crystalline rocks that border certain shores and that have by disintegration, decomposition, and transportation reached the lake waters in solution. In all the calcium and magnesium analyses that Gorton made of the lake sediments by digestion in *HCl* (in tables in this chapter and others), a very perceptible iron precipitate appeared. It may not have been sufficient in some, even though in the ferric oxide state, to produce a conspicuous red color but in others it seemed enough. It must be concluded that the alkaline (pH 7.4 to 8.48) and saline waters of Great Salt Lake reduce the more soluble ferric compounds and prevent the appearance of red coloring in the sediments.

SUMMARY

The soft plastic sediments of the lake, on a carbonate-free basis, are classified as clays and loams because of their high content of small particles. They occur in the central lake areas below a depth of 12 feet and under shallower water in embayments protected from wave action, and at river mouths.

The clays are exceptionally smooth and plastic which property is due chiefly to the base ions, particularly Na^+, attached to the clay particles. In the alkaline and very saline environment of Great Salt Lake sodium clays result. This may not be the sole cause of plasticity but is a very important contributing cause.[49]

[49] Oral communication, M. W. Senstius, University of Michigan. See also pp. 1375–78.

The three groups of clays, namely, the river-mouth clays, the deep-lake clays, and the near-shore clays of the western division of the lake have approximately the following constitution and origin.

RIVER-MOUTH CLAYS OF EASTERN DIVISION

		Per Cent
Clastic material, chiefly clay and silt particles greater than colloidal size, transported by lake currents from rivers		25
Clastic material, chiefly clay and silt particles, transported by the wind and deposited by lake		32
Organic matter		1.5
Precipitated from solution	Aragonite ($CaCO_3$)	15
	Dolomite ($CaCO_3 \cdot 2MgCO_3$)	5
	Parasepiolite (?) ($2MgO \cdot 3SiO_2 \cdot 4H_2O$)	7
	Absorbed bases (*Ca, Mg, Na, K*)	6+
Precipitated from colloidal suspension	Montmorillonite (?) and other colloidal mineral particles, transported by rivers and lake currents	8
	Total	100.5

DEEP-LAKE CLAYS OF WESTERN DIVISION

		Per Cent
Clastic material, chiefly clay and silt particles greater than colloidal size, transported by lake currents from rivers and shore lines		6
Clastic material, chiefly clay and silt particles, transported by the wind and deposited by the lake		40
Organic matter		2
Precipitated from solution	Aragonite ($CaCO_3$)	26
	Dolomite ($CaCO_3 \cdot 2MgCO_3$)	4
	Parsepiolite (?) ($2MgO \cdot 3SiO_2 \cdot 4H_2O$)	7
	Absorbed bases (*Ca, Mg, Na, K*)	9+
Precipitated from colloidal suspension	Montmortillonite (?) and other colloidal mineral particles, transported by rivers and lake currents	5
	Total	100

NEAR-SHORE CLAYS OF WESTERN DIVISION

		Per Cent
Clastic material, chiefly clay and silt particles greater than colloidal size, transported by offshore currents		8
Clastic material, chiefly clay and silt particles, transported by the wind and deposited in the lake		55
Organic matter		1
Precipitated from solution	Aragonite ($CaCO_3$)	13
	Dolomite ($CaCO_3 \cdot 2MgCO_3$)	6
	Parasepiolite (?) ($2MgO \cdot 3SiO_2 \cdot 4H_2O$)	6
	Absorbed bases (*Ca, Mg, Na, K*)	4+
Precipitated from colloidal suspension	Montmorillonite (?) and other colloidal mineral particles, transported by rivers and lake currents	7
	Total	100

The percentages in the three groups of clays were computed as follows. The general divisions of page 1352 were used as the basis. Montmorillonite (?) was determined from Tables VIII and XII, that is, if, for sample I, montmorillonite (?) equals 27.7 per cent of the fine white material (Table XII), and the clay fractions of the river-mouth samples, H and I (Table VIII), average 21.6 per cent, then

21.6 per cent of 27.7 per cent equals 6 per cent of montmorillonite (?) for the river-mouth clays. As some of the montmorillonite (?) flakes are larger than clay-size and as the clastic fraction transported by lake currents is large, 2 per cent more has been arbitrarily added to 6 per cent for the river-mouth sediments. This was not done in the other two groups inasmuch as the lake-current-transported fraction is small. The amount of montmorillonite (?) thus determined was subtracted from 43 per cent (for the river-mouth samples) leaving 35 per cent for the amount of clastic material above colloidal size transported by lake currents.

The chemical precipitates for each group of clays were found by proportioning the amounts shown in Table XII into the percentage figures of page 1352, which show the total soluble content. In Table XII, sample I represents the river-mouth clays, Q and Z the deep-lake clays, and U the near-shore clays of the western division of the lake.

The organic matter was taken from Table X. As organic matter was not considered in the general estimates on page 1352, the addition of this material in the more detailed tabulations brings the total percentage to more than 100 per cent. In order to obviate this condition the amount of organic matter from each group was subtracted from the wind-transported percentage. The wind-transported fractions are not very accurate and they are large enough so as not to be affected materially by the slight reductions involved. The procedure is in part justified because considerable fragmental plant material is part of the dust that settles into the lake. An examination of the particles obtained from the dust catcher erected on Promontory Point showed plentiful plant tissue and spores.

The CaO:MgO ratio of the soluble contents of the river waters that empty into the lake is about 2.6:1. The weighted ratio of the same oxides soluble in weak hot HCl from all of the lake sediments is 7.3:1. This difference can not be accounted for by continued concentration of magnesium in the lake waters, but is understood, at least in part, by base-ion absorption of Mg^{++} ions in greater proportion than Ca^{++} ions in and around the various colloidal particles of the lake clays.

Sodium and potassium are being absorbed likewise by the clays but in amounts five or six times as great. Under existing conditions it is possible that K^{+} ions may never become more concentrated in the lake waters than at present, although the streams continue to empty potassium salts into the lake.

The average moisture content of the clays is 39 per cent on a total-weight basis. Compaction and dehydration appear to be occurring

even at shallow depths. A crude hexagonal fissure system is an interesting consequence at two places, as are also the effects of a recent earthquake in liberating cold salt water in fissures around an almost buried bedrock hill.

The identifiable minerals are the common detrital ones, with quartz most plentiful. They reflect the nature of the rocks of the nearest shore, but probably contain some admixture from more distant regions by wind transportation.

Bacteria appear to be active in almost all of the clays because of the sulphurous fumes emitted but the diagenic effect on the carbonate and organic content, and this in turn on the color and laminations, is not known. From samples taken at increasing depth down to 20 feet no change could be recognized physically or chemically except for less water and, under the black surface oozes, less organic content.

The lake waters are probably reductive to iron compounds and prevent the appearance of red coloring in the sediments.

OÖLITES

DISTRIBUTION

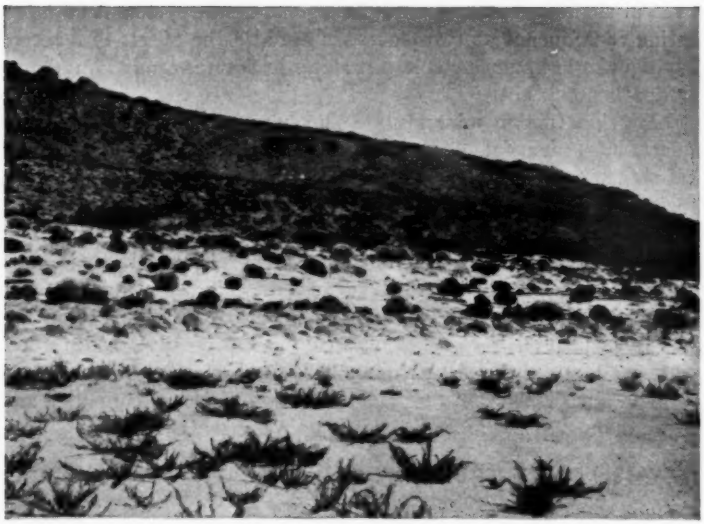
Oölites have been collected from the lake shore since the time of the U. S. Geological Exploration of the 40th Parallel[50] but Talmage[51] is the only writer on the subject to note their confinement to the shore areas. This observation was verified by the writer in mapping the distribution of the different sediment types of the lake (Fig. 2). However, not all the shores contain oölitic sand. The eastern part of the lake is practically devoid of it, whereas the oölites are very plentiful along most of the shore line of the larger western part. They have been thrown up in storm beaches in several places, conspicuously so northwest of Rozell Point (locality A) and Promontory Point (locality E), and hence have drifted inland by the force of the wind and form either low sand dunes, several yards in height,[52] or level sandy stretches treacherous for automobile travel (Pl. 5).

Shore lines which face the open lake and receive the unimpeded waves are invariably the most favorable for oölite development. The largest oölites of the lake are found on a bar off the southwest end of Antelope Island (Pl. 6b and locality S) which is washed by the open lake waves driven by the most prevailing winds, the northwesterlies. Ripple marks are well developed where oölitic sand exists. Dredgings from the lake show the sandy oölitic bottom to extend from the

[50] Vol. 2 (1877), p. 435.

[51] J. E. Talmage, *op. cit.*, pp. 65–66.

[52] J. E. Talmage, *op. cit.*, p. 6[illegible].

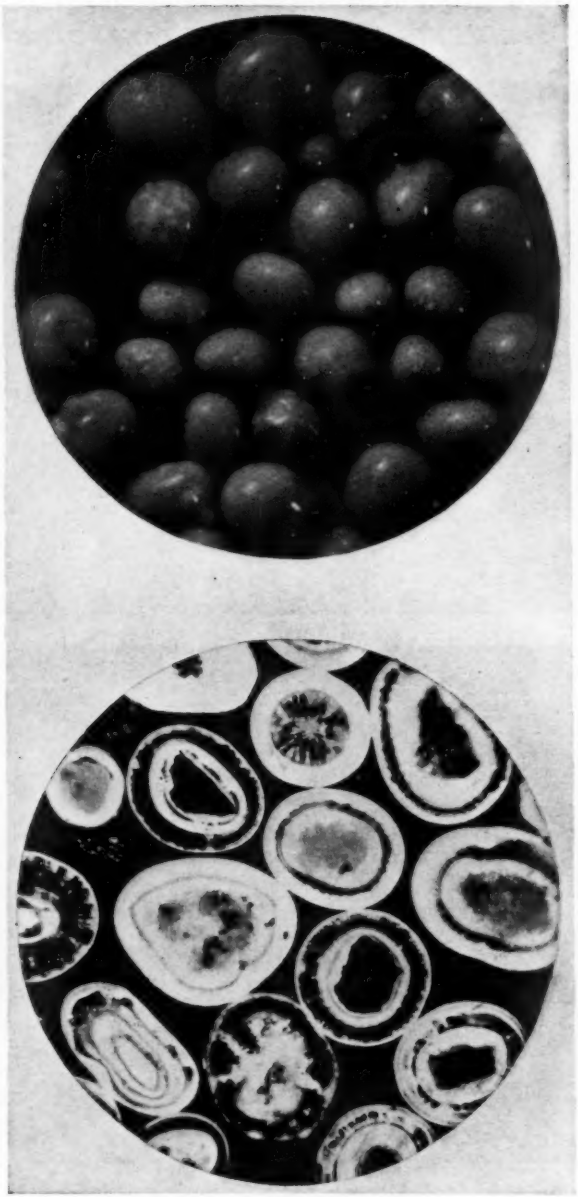


PL. 5a.—Storm beach and longitudinal oölitic sand dune ridge, on southwest end of Promontory Point. Small figure of man on dune indicates dimensions.
b.—Oölitic sand beach at Rozell Point, locality A, Fig. 2.

shore line lakeward to a depth ranging from 3 to about 12 feet (lake level, 1933).

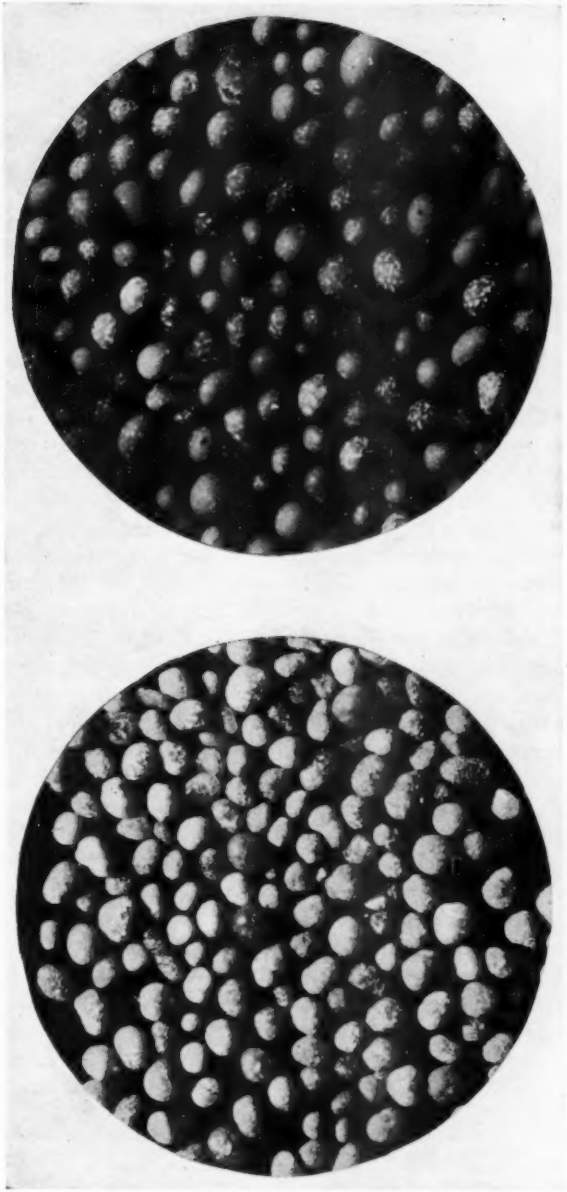
PL. 6a.—Aerial view looking northwest from west shore of Promontory Range to Rozell Point in distance. Terraces above present shore line are those of Lake Bonneville levels. White offshore areas are chiefly oölitic sand.

b.—Aerial view, looking north, of prominent spit of coarse oölitic sand built out from southwest end of Antelope Island. Promontory Range in distance.



PL. 7a.—Photomicrograph of oölites from locality S, Fig. 2, exterior view of oölites having smooth surfaces. Enlarged 15 diameters.

b.—Same oölites as in *a* but in thin section. Small oölite in upper central part shows radial structure in faecal pellet nucleus. Enlarged 25 diameters and photographed in reflected light.



Pl. 8a.—Photomicrograph of exterior of mottled oölites, from locality K, Fig. 2. Enlarged 15 diameters.
b.—Mottled oölites from locality R, Fig. 2. Enlarged 15 diameters.

DESCRIPTION

Shape and size.—The oölites tend toward sphericity in form but few are truly spherical, ordinarily having one axis longer than the other two. This is commonly a reflection of an initially elongate nucleus. They range in size in long diameter from 0.15 to 1.5 millimeters. The variation is, however, not this much in any one locality, and small oölites are found almost exclusively in one place and large oölites in another. The largest oölites that were found anywhere in the lake came from the bar on the west shore of Antelope Island already referred to, where the average diameter is 0.8–1.0 millimeter. At Johnson's Ranch the range is 0.18–0.54 millimeter, averaging about 0.31 millimeter. This latter figure is representative of most of the Great Salt Lake oölites. Mathews[53] gives the size of oölites collected from the west shore of Stansbury Island as 0.14 to 0.63 millimeter (100-mesh to 20-mesh per inch). It should be noted that the size of the oölites in thin section is somewhat smaller than that of the actual.[54] The writer's figures were obtained by measuring the whole oölites with a stage micrometer using a petrographic microscope.

Mathews[55] also states that the oölites increase in size the farther they are drifted landward by the wind and he, therefore, correlates size with wind activity. He measured oölites obtained from only one locality and neglected the storm beach with its coarser assortment of oölites, and may not have differentiated temporarily exposed lake bottom from the true beach at the "bluff line" (pp. 1315–16). The storm beach generally furnishes the sand for wind transportation[56] but only the finer material is blown landward. This was observed at Rozell Point and the west side of Promontory Point.

In some localities the oölites have very smooth and pearl-like surfaces (Pl. 7a) but others are mottled or pitted (Pl. 8). Ordinarily some pitted oölites may be seen among those that are pearly smooth.

Nuclei.—In thin section, all the oölites studied consist of two parts, namely, the nucleus and the concentric bands or layers. In some the radiate structure is strongly developed through the bands. (Pls. 7b, 9a and b, and 10.)

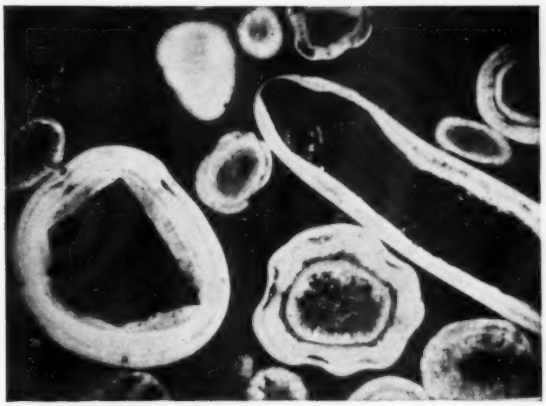
The nuclei of the oölites are mineral fragments, similar to the common detrital minerals in the clays, and small, opaque white

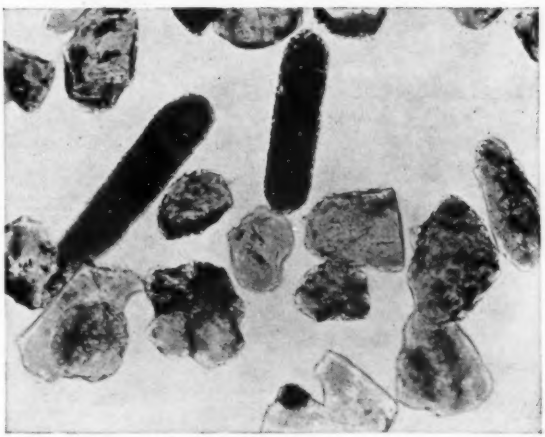
[53] A. A. L. Mathews, "Origin and Growth of the Great Salt Lake Oölites," *Jour. Geol.*, Vol. 38 (1930), p. 639.

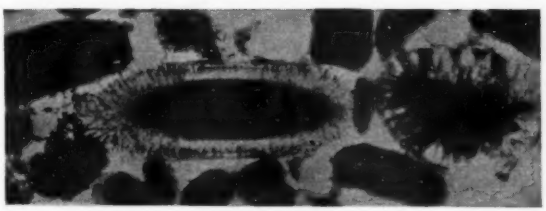
[54] The theoretical relationship for spherical bodies is: $d/\cos 30° = S$ or $S = 1.1547od$ where d is the thin-section diameter and S is the actual diameter.

[55] A. A. L. Mathews, *op. cit.*

[56] Personal communication from I. D. Scott, University of Michigan, who has studied the Lake Michigan sand dunes.



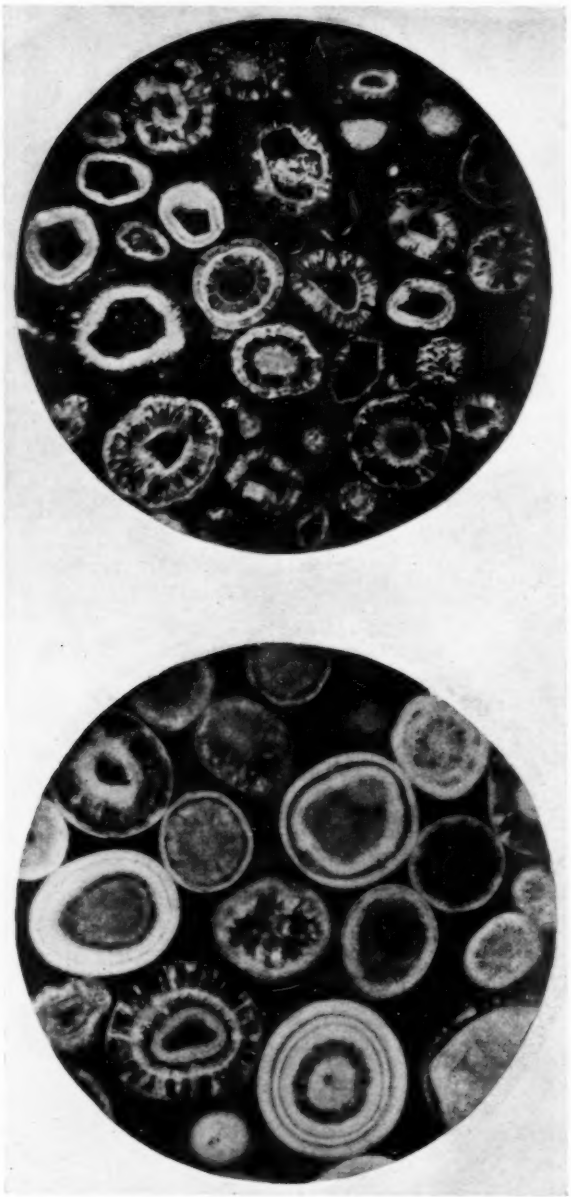




PL. 9a.—Large oölites showing reflection of irregular-shaped mineral fragment nuclei. Locality S, Fig. 2. Enlarged 35 diameters and photographed in reflected light.

b.—Quartz fragments which were nuclei of oölites but released by solution in *HCl*. Also clay remains of faecal pellets. From locality E. Enlarged about 60 diameters and photographed in transmitted light.

c.—Faecal pellet with radiating lamination. Section is cut at acute angle to longitudinal axis of pellet. Enlarged about 60 diameters and photographed in transmitted light.



PL. 10a.—Thin section of oölites shown in exterior view in Plate 8b. Secondary radial structure is strongly developed. Photographed in reflected light and enlarged 35 diameters.

b.—Thin section showing radial structure well developed in some oölites and poorly developed in others. Most oölites have faecal pellets as nuclei. Central oölite shows inversion of nuclear faecal pellet with tendency toward radial structure. Photographed in reflected light and enlarged 35 diameters. Locality A.

stubby, rod-like bodies. The rod-like bodies are the faecal pellets of the brine shrimp and are described in detail on pages 1401–08. Some of the pellets are so thoroughly radiate that the oölite may appear not to have a nucleus. Quartz fragments are the most common of the mineral particles, with orthoclase and calcite next. Surprisingly large amounts of the heavy minerals are present, such as ilmenite, magnetite, pyrite, leucoxene, and garnet. A list of the minerals identified from each locality is shown in the chart of Table IX. Most of the determinations were made by W. F. Hunt of the University of Michigan.

Plate 9b shows nuclear fragments after the concentric calcareous layers have been removed by solution in *HCl*. The minerals present in the nuclei reflect to a noticeable degree the nature of the adjoining land surface. At Rozell Point the basalt cliffs have contributed small basalt, hematite, and magnetite particles. On the west shore of Antelope Island mica flakes are conspicuous and come from the schists and gneisses that chiefly compose the island. At Promontory Point where the Brigham quartzite and the Algonkian(?) quartzites and other metamorphic rocks crop out, the mineral particles are chiefly quartz.

In addition to the nucleus minerals noted by the writer, Mathews[57] has listed cinder, copper, coal, soot, and "opaque masses." These determinations have not been confirmed because Mathews' table does not give the locality from which the samples were taken.

Concentric bands. Optical properties.—The concentric bands are white under reflected light but when viewed under the petrographic microscope in transmitted light are dark or black except in exceptionally thin sections, indicating the bands are merely opaque. Where radial bars are present across the bands the opacity is lost and the bars prove to be transparent, colorless crystals that are chiefly calcite. C. B. Slawson of the Department of Mineralogy assisted in this determination and found the indices of the crystals that were large enough for positive identification identical with those of calcite. This index of refraction determination was not positively confirmed by the new microscopic test recently described by Leitmeier and Feigl,[58] and it is possible that in some of the oölites the smaller radial crystals are aragonite. The opaque bands, or those parts of bands remaining between the transparent calcite or aragonite rays, are composed of cryp-

[57] A. A. L. Mathews, *op. cit.*, p. 634.

[58] H. Leitmeier and F. Feigl, "Eine einfache Reaktion zur Unterscheidung von Calcit und Aragonit," *Zeit. für Krist., Min., und Pet.*, Abt. B., Band 45, Heft 5/6 (1934), pp. 447–56.

tocrystalline aragonite with occluded fine white clay. The chemical analyses give more information on the clay part and are referred to on a following page. The aragonite determination was made first by the simple cobalt nitrate test. Later this was confirmed by an X-ray analysis made by L. S. Ramsdell of the Department of Mineralogy of the University of Michigan. The X-ray photograph is shown in Plate 12c. According to Ramsdell the dark negative indicates the aragonite to be cryptocrystalline.

That the primary precipitate is aragonite is in accord with beliefs of Johnston, Merwin, and Williamson.[59] They state that alkaline conditions are prejudicial to the formation of calcite and consequently promote the appearance of the commonly less stable form, aragonite. Alkaline conditions prevail in Great Salt Lake, the waters having a pH of 7.4 to 8.4 showing an excess of OH^- ions.[60] Another favorable condition for the formation of aragonite in nature at normal temperature, they believe, is the presence of saline waters containing sulphate ions. These conditions are also satisfied in Great Salt Lake.

The opaqueness and whiteness of the concentric bands is due first, to the cryptocrystalline aragonite and second, to the mechanically enmeshed clay particles between the aragonite crystals. As reflected light reveals the chemical and optical properties of the oölites best it has been used in making most of the photographs in the accompanying plates. A comparison of the same oölite photographed in transmitted and reflected light is shown in Plate 11. Mathews[61] believed that the concentric rings were black and has attempted to account for the black coloring in them, but no black material was present in any of the oölites examined by the writer.

Chemical analysis.—The chemical properties of the oölites, except for organic matter, are given in Tables XV–XVIII. The organic matter of the Saltair oölites (locality K) was determined by H. E. Hammar of the American Petroleum Institute under the direction of P. D. Trask. It amounted to 0.54 per cent.

The calcium and magnesium content, soluble in weak, hot *HCl*, appears to be united, without excess, with CO_2, and differs in this respect from the clays. In fact, an excess of CO_2 remains when the combining ratios of MgO and CaO are satisfied. This is shown in Table

[59] John Johnston, H. E. Merwin, and E. D. Williamson, "The Several Forms of Calcium Carbonate," *Amer. Jour. Sci.*, 4th Ser., Vol. 41 (1916), p. 506.

[60] Seville Flowers, "Vegetation of the Great Salt Lake region," *Bot. Gaz.*, Vol. 95 (1934), p. 359. Flowers gives the pH as 8.3 but the more recent work of Bonner (see section on Chemistry) shows the pH to range from 7.4 at high salinity, to 8.4 diluted 6 or 7 times.

[61] *Op. cit.*, p. 634.

XVII. The MgO was first united with CaO and CO_2 on the basis of a dolomite having the same composition as the dolomite in the clays, namely, $2MgCO_3 \cdot CaCO_3$. No magnesium carbonate mineral was detected under the petrographic microscope but it must exist, since the chemical analyses show considerable acid-soluble magnesium present. The dolomite precipitating out of the lake waters in the clay is the only guide available for the calculation of magnesium carbonate in the oölites.

TABLE XV

CaO, MgO, CO_2, Clay, and Nuclei Content of Great Salt Lake Oölites

Sample	*CaO*	*MgO*	CO_2	*Clay Per Cent*	*Nuclei Per Cent*	
Map Location	*Soluble in Weak Hot HCl*		*With Ca and Mg as Aragonite and Dolomite*	*Occluded in Carbonates*	*Mineral Fragments. See Table IX*	*Description of Sample*
A_1				6.5	5.5	Dark gray oölites from Rozell Point
A_2				7.2	4.8	Light gray to pearly white oölites from Rozell Point
K	45.8	2.0	39.1	6.5	7.6	Light gray oölitic sand just north of Saltair, water 1 foot deep. Foreign mineral particles removed but some small faecal pellets still remained
N	48.3	2.3	40.6	7.6	1.2	Light gray oölites collected in 8 inches of water west of Carrington Island
R	45.3	1.5	37.3	4.1	11.8	Small oölites one mile SW. Antelope Island in 2½ feet water
S	47.0	1.4	38.7	1.7	11.2	Large pearly oölites from bar on SW. end Antelope Island in 1 foot water
Average	46.6	1.8	38.9	5.6	7.0	

CaO and *MgO* analyses by K. A. Gorton, University of Michigan. The powdered oölites were treated with weak, hot *HCl*, and the *Ca* and *Mg* thus dissolved are represented. Gorton also assisted in making an approximate separation of the clay and nuclei which constitute the insoluble fraction in dilute *HCl*. The figures for these two fractions are approximate. The CO_2 figures were found by difference. They were checked approximately by Professor Senstius, and correspond favorably with those of Table XVI.

After satisfying the MgO with CaO and CO_2, the remaining CaO was united with CO_2 and a small amount of CO_2 was unused. If the magnesium were present as magnesite ($MgCO_3$) then slightly less CO_2 would remain in excess. If some of the CO_2 came from organic matter (0.54 per cent present in Saltair oölites), then the CO_2 excess would be reduced still more. The significance of the apparent small excess of CO_2 over the combining ratios of CaO and MgO is not known, but it is safe to conclude that no excess calcium and magnesium is obtained from the oölites by digestion in weak, hot *HCl*. However,

TABLE XVI

CHEMICAL ANALYSIS OF GREAT SALT LAKE OÖLITES

	Black Rock[1]	*Black Rock*[2]	*Locality not Given*[3]
Al_2O_3	0.18		
Fe_2O_3	0.31	·.27	.20
CaO	51.44	51.41	51.33
MgO	1.02	.92	.72
Na_2O	0.38	.75	
K_2O	0.12	.34	.63
CO_2	40.83	40.74	41.07
P_2O_5	0.065		Trace
SO_3	0.55	.53	.89
H_2O	1.78	1.28	.83
SiO_2	3.03		
Cl	Trace		
N	0.03		
As_2O_3	0.012		
TiO_2	0.0065		
Insoluble residue	None	3.86	4.03
Organic matter			.27
	99.75	100.10	99.97

[1] By George Cronkheit. Analysis made during summer of 1935 at the University of Utah. The sample was washed free of all save a slight trace of chlorine ions, and completely free of sulphate ions, but in no other way selected or graded.
[2] *U. S. Geol. Explor. 40th Par.*, Vol. 2, p. 435.
[3] *U. S. Geol. Survey Bull. 228*, p. 331.

TABLE XVII

CALCULATED CARBONATE CONTENT OF OÖLITES

Mineral	*Oxide*	*Locality*		
		L	*N*	*S*
Dolomite ($2MgCO_3 \cdot CaCO_3$)	MgO	1.6	2.3	1.4
	CaO	0.6 } 3.2	1.5 } 7.6	0.9 } 4.6
	CO_2	1.6	3.8	2.3
Aragonite	CaO	50.8 } 90.7	46.8 } 83.3	46.1 } 82.3
	CO_2	39.9	36.5	36.2
Excess CO_2	CO_2	0.92	4.1	2.5

Sample L was calculated from Cronkheit's analysis, Table XVI, and samples N and S were calculated from Table XV.

absorbed bases not extractable by weak acid treatment are present in the enmeshed clay complex of the carbonate bands (Table XVIII), and are discussed later.

Regarding the carbonate analyses three facts are conspicuous. First, the carbonate content is fairly uniform in all oölite samples analyzed, not varying more than 3 per cent of the average (figured on the basis of Tables XVI and XVII). Second, the oölites contain an average of more than twice as much carbonate as the clays and loams

(oölites, 89 per cent and clays, 35 per cent, see p. 1353). Third, the ratio of *CaO* to *MgO* is higher for the oölites than for the clays (oölites, 26:1 and clays, 3.3:1).

The ratio of total carbonate (acid-soluble basis) to "occluded" clay in the oölites is 15.6:1. On the other hand, the plastic clays and loams of the lake have a ratio of about 2:1 (see p. 1349). The clays, therefore, contain about 7 times as much fine white material (the clay complex) as the oölites.

ORIGIN

The origin of the concentric oölites of various parts of the world and of various geological ages has received much attention. The present inquiry draws freely from the observations and conclusions of investigators of various oölitic deposits but, at the same time, the theory of origin presented is proposed solely for the oölites of Great Salt Lake.

Summary of descriptive facts.—The facts believed relevant to a theory of origin may be summarized as follows.

1. Oölites are found only along the shore lines. They form a zone extending lakeward into water ranging in depth from 3 to 12 feet and in some places landward as far as 0.5 to 1 mile. This latter distance does not include the stretches laid bare by recession of the lake —it represents the distance beyond the bluff-line,—where the oölitic sand has been blown by the wind (pp. 1315–16).

2. The shores where oölites are most plentiful are those exposed freely to the open lake where large waves are active. Other shore lines not exposed to the open lake or those along the shallow eastern part either have very little oölitic sand or none at all.

3. Well developed ripple marks are invariably found where oölitic sand exists.

4. The more vigorous the wave activity the larger and more typically developed the oölites and ordinarily the cleaner the oölitic sand.

5. Physically the oölites consist of two parts, nucleus and concentric layers about the nucleus.

6. The nuclei consist of mineral particles, chief of which are quartz and small rod-shaped forms—the faecal pellets of the brine shrimp, *Artemia gracilis*. The mineral grains are rarely frosted, commonly angular, and their unequal dimensions are reflected in the shape of the oölite, but the concentric layers each in turn gradually subdue the original nucleus shape. The nucleus minerals conspicuously betray the mineral composition of the neighboring landmass, but there is thought to be some regional admixture of wind-blown material. The size of the

nuclei varies approximately in inverse proportion to distance from the source rock—the smaller the nuclei, the farther away from shore.

7. The concentric layers are white and quite opaque, except in exceptionally thin sections. Many, but by no means all, of the white opaque layers are intersected and traversed normally by radiating rays of a colorless, transparent mineral, ordinarily calcite but probably in part aragonite in some oölites. The rays may be confined to certain layers, commonly the inside ones, leaving others, ordinarily the outer, entirely dense.

8. The size of the oölite depends on the size of the nucleus, the number of concentric layers, and the thickness of the layers. The size of the nucleus is somewhat related to shore conditions. Larger nuclei are found close to steep shores like those of Antelope Island than along very gentle sloping shores like those of Saltair.

9. The concentric layers consist of about 84 per cent of $CaCO_3$, 5.5 per cent of $2MgCO_3 \cdot CaCO_3$, and 5.6 per cent of very fine clay. The dense carbonate mineral is cryptocrystalline aragonite. The small amount of $MgCO_3$ probably exists in the state of dolomite in mechanical admixture with the aragonite because the magnesium atom is too large to fit into the space lattice of either calcite or aragonite.[62] The composition of the dolomite in the oölites is not known but is assumed to be the same as in the clay, *viz.*, $2MgCO_3 \cdot CaCO_3$.

10. The radiating, transparent crystals are probably calcite. They are free or nearly free from clay. Single crystals commonly transgress many concentric layers but again may terminate abruptly against a surrounding layer.

11. The oölites are either pearly smooth on the outside surface or are mottled to various degrees. The oölites from some localities are mostly smooth whereas from others they are mostly mottled.

12. Those oölites in which radiate structure is highly developed and extends to the surface are the most mottled. Conversely, those having dense white layers on the outside possess smooth pearl-like surfaces.

Physical chemistry of carbonate accretion.—From facts 1, 2, 3, and 4 it is evident that the origin of the oölites is to be correlated with somewhat vigorous wave activity, particularly the oscillatory motion at the bottom. It has also been shown that calcium and magnesium carbonate are being precipitated on the lake bottom. These two processes are believed to work together to build oölites. The carbonate is first precipitated as minutely small crystals near the surface of the

[62] Personal communication from L. S. Ramsdell, Department of Mineralogy, University of Michigan.

water because of evaporation (see section on chemistry). These carbonate crystals sink and on reaching the bottom are more soluble than the larger particles (the oölites already in process of growth) and are redissolved. At the same moment molecules of carbonate come out of solution and build on the larger particles which are less soluble. The theory involves the phase rule and is based on the observation of variable solubility of a substance depending on the degree of comminution.[63] When the grain size of $CaCO_3$ particles is less than 2 millimeters the solubility noticeably increases.[64] In other words, when a solution is saturated with respect to fine grains, it is supersaturated with respect to larger grains. The larger particles grow at the expense of the smaller. Both algal photosynthesis and bacterial metabolism may alter the pH of the lake waters and result in carbonate precipitation. These undoubtedly are contributing factors but the extent to which they are operative in the areas of oölite growth can not be determined until further work on the lake flora has been done, and it is not essential to invoke their aid.

The constant agitation by the waves of the oölites or sand particles in the troughs of the ripple marks, which are everywhere a part of the oölitic sand deposits in Great Salt Lake, causes them to be rolled over and over, each time exposing new surfaces for accretion of carbonate molecules. Layers of uniform thickness are thus built up. The constant agitation prevents supersaturation to any great extent but works toward equilibrium in immediate response to concentration and precipitation as effected by evaporation.

Distinct layers instead of one continuous "growth ring" are the rule because of seasonal climatic variations which alter the rate of carbonate precipitation. In the section on chemistry it was concluded that the period of maximum $CaCO_3$ precipitation coincides with the period of greatest evaporation, namely, from June to November. The period of the year from February to May, during the maximum inflow with resulting dilution, will be one of little or no precipitation of $CaCO_3$ in most parts of the lake. In fact, some solution of the smallest crystals might occur. This period of much slower growth or no growth at all of the oölites probably produces a different texture on the outer surface. Such a feature, combined with the development of a secondary radial structure discussed later, produces distinct rings or layers.

The annual cycles of carbonate precipitation may be superposed on larger ones of 30 to 45 years duration (Fig. 3). With rising lake level over a period of years the water volume increases and the salinity de-

[63] G. A. Hulett, *Zeit. Physical Chem.*, Vol. 37 (1901), p. 385.

[64] Julius Pia, "Die Binnengewässer," *Kohlensäure und Kalk*, Band 13 (1933).

creases. Although the solubility of $CaCO_3$ decreases with decreasing salinity, the greater volume of water more than offsets the decreasing solubility factor and a greater amount of $CaCO_3$ remains in solution than in less volume and greater salinity (see pp. 1326–28). Each summer during the evaporation hemicycle, as part of a major hemicycle of lake rise, only a part of the carbonate will be precipitated that was brought into the lake by the rivers during the maximum inflow period. This should result in thinner concentric layers on the oölites during a general rise of the lake level and thicker layers during a time of general recession. The deduction may find confirmation in the well developed and in many places beautifully layered oölites found on present shores, after the last 15-year period of lake-level decline.

Contrary to Mathews'[65] conclusion that "soot particles" from Salt Lake City during the winter time produce the rings, the writer failed to discover any soot and suggests that Mathews' "soot particles" were probably the white opaque layers which appear quite black in transmitted light. The same layered structure exists in the oölites in the north end of the lake, about 100 miles from Salt Lake City, as at Saltair which is only 18 miles away.

Mathews believed that the oölites originate by wind activity on the "mud flats" beyond the water's edge where it was thought "capillary water" on evaporation would deposit a film of carbonate about the nucleus. Wind does not drift sand or silt on moist surfaces,[66] and so it appears to the writer that capillary water could, at best, cement the particles together. *NaCl* is the chief salt in solution in capillary waters of the lake bottom exposed during periods of low lake level. It forms extensive crusts during the hot summer months. These crustiform *NaCl* deposits make improbable the process of oölite formation that Mathews proposes (Pl. 4b).

Mechanical relation of clay to carbonate.—The clay is probably not in chemical combination with the calcium and magnesium carbonate. When the carbonate is dissolved with dilute *HCl* the clay is liberated as a fine, light, flocculent material which settles slowly, suggesting that the clay may be mechanically enmeshed in the carbonate crystals and (or) that a hydrous magnesium silicate has been broken down to colloidal silica by the acid (see section on origin of clays). Heretofore, where the term "occluded" has been used, the idea of "mechanically enmeshed" is inferred. Enmeshing is mentioned in the discussion

[65] *Op. cit.*, p. 634.

[66] Personal communication, I. D. Scott, Department of Geology, University of Michigan.

of the supposed $CaCO_3$ form, "Vaterite," in which Johnston, Merwin, and Williamson[67] come to the conclusion that the substance

> consists essentially of radiating prisms of calcite too fine to be resolved by the highest powers of the microscope; the individual calcite fibers are not all in actual contact—for, when crushed, the aggregates fall apart along radial lines—the water (and other impurities) is merely enmeshed in the very small interstices among the fibers . . .

These authors were not sure whether the sub-microscopic fibers are calcite or aragonite. A certain experiment suggested aragonite as the original form reverting to calcite[68] later. The present writer believes the clay to be enmeshed between small aragonite crystals in a similar manner. When the oölites of the Great Salt Lake are viewed in polarized light the well crystallized or distinctly rayed bands form an extinction cross indicating, as the structure suggests, that the calcite fibers are almost parallel to their neighbors but at the same time perpendicular to the quasi-spherical surface of the oölite. If bands which are progressively less distinctly crystallized are observed for the property of extinction it will be noted that there is a gradual transition to ones that are opaque or "amorphous."[69] It would be impossible to distinguish, then, those bands that have radial structure from those that do not. In fact, it is here suggested that the original form and position of the acicular aragonite crystals is normal to the surface on which they grow. Sorby[70] postulated an antithetical orientation of the aragonite crystals in the pisolites from Carlsbad which grow as if minute needles of aragonite were laid tangential to the surface. His postulation made in 1879 is based on no tangible evidence as far as the writer can discern.

The X-ray photographs indicate the aragonite to be definitely crystalline but probably submicroscopic or cryptocrystalline.

The ratio of the inclosing carbonate crystals to the enmeshed clay is 15.6 to 1. More clay than this would, perhaps, prevent sufficient interlocking of the aragonite crystals to form a crystalline texture with appreciable solidity. It will be remembered that the plastic calcareous lake clays contain seven times as much of the fine, white, flocculent clay complex as do the oölites which together with high moisture content may prevent crystallization and hardening.

[67] John Johnston, H. E. Merwin, and E. D. Williamson, "The Several Forms of Calcium Carbonate," *Amer. Jour. Sci.*, 4th Ser., Vol. 41 (1916), p. 488.

[68] Since the X-ray method was not used, the determination was not positive.

[69] Johnston, Merwin, and Williamson, *op. cit.*, pp. 490–91.

[70] Sorby, *Quar. Jour. Geol. Soc.*, Vol. 35 (1879), p. 56.

Chemical relation of clay to carbonate.—The colloidal status of the fine, white, kaolin-like clay of the concentric bands may be speculatively deduced but experimental work by the colloidal chemist has not yet proceeded far enough in the system involved to allow final conclusions to be drawn. Any particle less than 350 microns in the oölites falling from the atmosphere or washed by streams into the lake will have a negative charge and will become surrounded by the cations of the brine.[71] Since these are mostly Na^{+} ions with a small percentage of Mg^{++} and Ca^{++} ions, the clay particle, according to soil chemists,[72] would appear in its simplest form as shown in Figure 6.

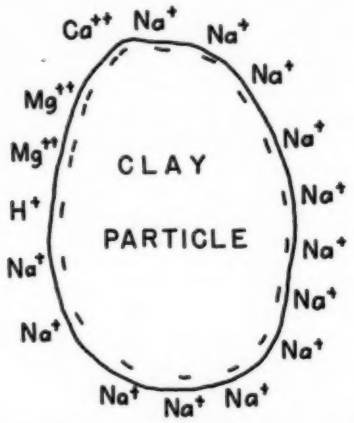


FIG. 6.—Physical conception of clay particle in waters of Great Salt Lake.

The clay particle with its cations may be regarded as a kind of salt in which the colloidal clay particle is the anion.

Certain cations may replace others making the clay more flocculent. The cation replacement is known as "base exchange." The specific precipitating order of various cations on certain suspensions have been determined and such a series is known as lyotropic. For clay suspensions the lyotropic series for cations is as follows.

Fe, Al, Ba, Ca, H, Mg, K, Na, Li.[73]

In great Salt Lake, "sodium type" clays are very plentiful and are characterized by their smooth sticky nature and their alkaline re-

[71] J. C. Ware, *The Chemistry of the Colloidal State.* John Wiley and Sons (1930).

[72] N. M. Comber, *An Introduction to the Scientific Study of the Soils*, p. 93, Edward Arnold and Company, London (1927).
M. W. Senstius, personal communication.

[73] M. W. Senstius, personal communication.

action (pH 7.4 to 8.4). The clay particles that became enmeshed in the carbonate crystals of the oölites accordingly probably existed also as sodium clay particles before occlusion.

The following laboratory experiment was performed on the occluded clay of the oölites in order to determine the flocculating or dispersing effect of the Mg^{++} and Ca^{++} ions in Great Salt Lake water.

The enmeshed clay from some oölites (locality B) was isolated and washed free of Ca^{++}, Mg^{++}, and Na^{+}, and most all H^{+} ions. The clay was treated with $NaOH$ until a pH slightly in excess of 8.4 was obtained. In this condition the clay particles were surrounded with Na^{+} (a few H^{+} may still have been present) in a solution of about the same alkalinity as Great Salt Lake. There were, however, no Ca^{++} and Mg^{++} ions as in the lake, and also fewer Na^{+} ions. The pure sodium clay solution was treated with about one volume of Great Salt Lake water (a check sample was kept for comparison) and evaporated to the concentration of the lake water. The check sample cleared in about 48 hours while the sample to which Great Salt Lake water was added cleared in 1 hour. The Mg^{++} and Ca^{++} ions appear to have displaced some of the Na^{+} ions and hurried precipitation of the clay particles.

In view of the previous comments regarding the "lyotropic series" and "base exchange" of cations on clay particles it follows that the Ca^{++} and Mg^{++} ions, while precipitating as the chemical compounds of calcium and magnesium carbonate, and building the minerals aragonite and dolomite, will attract and precipitate the sodium clay particles which remain for various lengths of time in suspension. This is a continuation of the precipitating process already begun by the Mg^{++} and and Ca^{++} ions in solution but the electrical and ionic interfacial relations and changes are too complex and too little agreed upon to permit further statements at present.[74] The premise seems warranted, however, that the aragonite surface will attract and hold the clay particle in the presence of the brine. The aragonite crystals are thought to be firmly attached to the oölite surface and while rolled back and forth by the waves, they become coated with films of clay particles smaller in size than 350 microns (see the following section on "Enmeshed Clay"). On the other hand, the clay particles may be coated with films of aragonite and dolomite crystals. In either case the clay particles would be in no way fundamental to concentric growth and their presence is due to ionic attraction and occlusion. They add to the whiteness and the opacity of the bands, however.

[74] Personal communications from M. W. Senstius and K. Fajans, University of Michigan.

By means of the same process that results in the coating of the growing aragonite crystals with fine clay particles, here and there small organic particles probably also become enmeshed in the bands of the oölites. Trask's analysis (p. 1364) reveals a small amount of organic matter in the oölites (0.54± per cent). It is believed that this organic content existed as individually suspended particles in the salt water much as the clay particles or any other disperse phase in an electrolyte, and through the process of base exchange, as with the clay particles, it became part of the film about each aragonite crystal of the growing oölite. The oölite sand bottom is adverse to blue-green algae attachment and none is found in the sand except a few hapless floaters. They are definitely not attached to the oölites or are the oölites embedded in the gel of the algae. The decaying algae, or perhaps even the live algae, may contribute small amounts of organic matter to the salt water which, through base exchange, may become part of the oölites.

Likewise, individual and free-swimming forms, such as the bacteria,[75] amoeba, and flagellates may possibly find attachment on the oölites but the agitation of the waves constantly rolling the oölites back and forth would be unfavorable to these organisms. No sulphurous emanations are given off from the oölitic sand as from the bottom clays and bioherms. This does not suggest an abundant bacterial flora in the oölitic sand. The bacteria, as the algae, may contribute minute particles of organic matter to the salt water in which form, if negatively charged, they would act the same as the clay particles and could become part of the oölites. The organic particles were too small to be observed in the oölites with about 400 times magnification.

Constitution of enmeshed clay.—The enmeshed clay particles range in size from less than 1 micron to 350 microns. Particles larger than 350 microns are seldom present and are either greater than the colloidal size for sodium chloride suspensions or too large to become enmeshed in the aragonite crystals. The "ultra-clay" particles which remained in suspension were generally smaller than 1 micron and exhibited Brownian movement very strikingly. An X-ray analysis by Ramsdell of the fine, settled clay shows weak quartz lines and one or two other anomalous ones. The silica content is, therefore, prominent but by no means the only crystalline substance present.

Peck of the Department of Mineralogy, University of Michigan, kindly studied the clay material with index liquids and found one

[75] According to Claude E. ZoBell of the Scripps Institution of Oceanography, in personal correspondence, the lake even at high salinities supports a rich indigenous bacterial flora. Most of the bacteria are periphytes which grow only when attached to some solid surface.

group of grains having an index of about 1.51 and another of about 1.54. The material of index 1.51 is so fine as to appear non-crystalline. It may be one of the bentonite minerals and for purposes of calculating the chemical analysis (Table XVIII) it has been assigned a composition of montmorillonite (see section on clays). The material of index 1.54 is also too fine for confirmatory optical tests, but the index and the X-ray analysis indicates quartz. There were also many very small individual grains of feldspar and quartz.

TABLE XVIII

CHEMICAL AND MINERALOGICAL ANALYSIS OF ENMESHED CLAY IN OÖLITES

Locality A

Constituent	*Per Cent*	*Mineral*		*Proportion of Oxides*		*Percentage of Total Sample*	
SiO_2	64.11	Quartz grains		SiO_2	100.0	15.00	
Al_2O_3 (includes TiO_2—Mn_3O_4	6.78	Colloidal clay complex	Colloidal silica(?)	SiO_2	100.0	27.79	
Fe_2O_3 (total iron)	3.42		Montmorillonite (?)	SiO_2	66.3	14.32	21.60
MgO	9.73			Al_2O_3	22.1	4.78	
CaO	1.27			CaO	1.9	0.41	
Na_2O	12.30			MgO	5.8	1.25	
K_2O	2.04			Fe_2O_3	3.9	0.84	
P_2O_5	0.16	Orthoclase and albite (1:1)		SiO_2	66.7	7.00	10.50
CO_2	0.30			Al_2O_3	19.0	2.00	
				K_2O	8.4	0.88	
				Na_2O	5.9	0.62	
		Aragonite		CaO	56.0	0.38	0.68
				CO_2	44.0	0.30	
		Apatite		P_2O_5	42.3	0.16	0.39
				CaO	55.5	0.21	
				$F(?)$	3.8	0.02	
		Fe_2O_3 as hematite, magnetite, and in ferromagnesian mineral grains		Fe_2O_3	100.0	2.58	
		Excess oxides (mostly absorbed bases in colloidal clay complex)		CaO		0.27	21.59
				MgO		8.48	
				Na_2O		11.68	
				K_2O		1.16	
Total	100.10			Total		100.13	

The enmeshed clay was analyzed chemically, the results of which are shown in Table XVIII.

The Al_2O_3 was spread between known feldspar and the bentonite mineral, supposedly montmorillonite, so that enough feldspar was present to equal approximately the amount of free quartz. The small amounts of CO_2 and P_2O_5 were satisfied with CaO, to form aragonite

and apatite. No attempt was made to calculate the Fe_2O_3 in terms of ferromagnesian minerals but it was considered to be present as hematite or magnetite because brown opaque grains could be discerned. About twice as much silica was assigned to the very finely crystalline material of index 1.54 as clastic quartz fragments, because the quartz fragments appeared less plentiful under the microscope. The material of index 1.54 may have been parasepiolite before treatment with *HCl* (see section on clays). The constitution of the enmeshed clay complex of the oölites, as shown in Table XVIII, is therefore, at best an approximation, but in light of available data it is probably not greatly in error. Greater complexity than simplicity can be anticipated. The colloidal (?) silica—before acid treatment, parasepiolite (?)—as part of the "enmeshed" clay adds complexity to the clay-carbonate relationship. Parasepiolite is probably a true chemical precipitate in Great Salt Lake together with aragonite and dolomite, and its colloidal properties and base ion associations are not known. Colloidal silica (?) constitutes about 28 per cent of the enmeshed clay, and if united with magnesium would make up about 40 per cent. The total parasepiolite (?) content of the oölites would then be 40 per cent $\times 5.6$ per cent (amount of enmeshed clay, p. 1371) $= 2.2$ per cent.

A large amount of *Ca*, *Mg*, *Na*, and *K* apparently remains in excess after the other various oxides have been satisfied. *Mg* and *Na* are surprisingly plentiful. This is another interesting relationship that will bear further study by the colloidal chemist.

Radial structure.—The following observations seem germane to the origin of radial structure in the oölites.

1. The same radiating calcite crystals sometimes pass through two or more concentric bands (Pls. 7, 10, and 12).

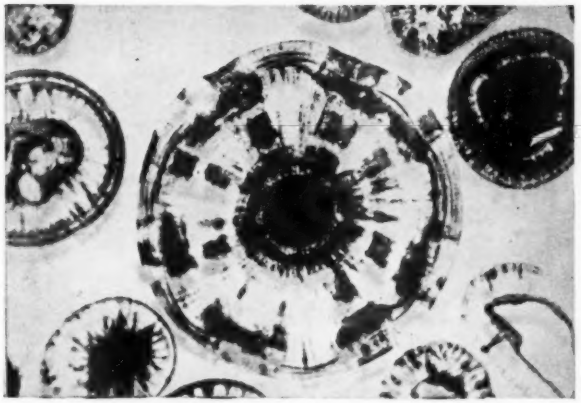
2. Part of an individual layer may be radially crystallized and the other part not (Pl. 12a).

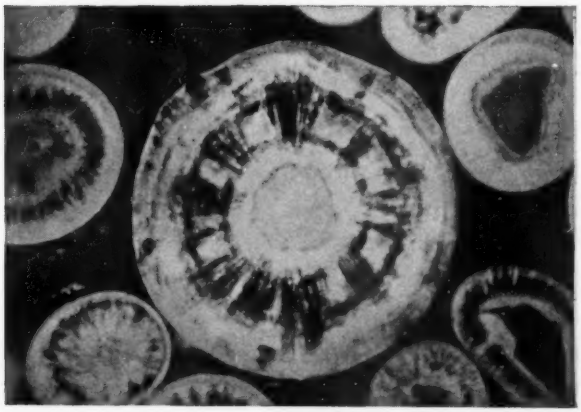
3. The older inner layers are ordinarily the most conspicuously radiating. The newer outer layers are ordinarily dense and opaque (Pl. 11).

4. Some oölites well crystallized and radiating throughout with only ghost layer lines may be cemented together with new layers (Pl. 12a). The newer outer bands are dense or only slightly crystallized in distinct contrast to the older radiating bands.

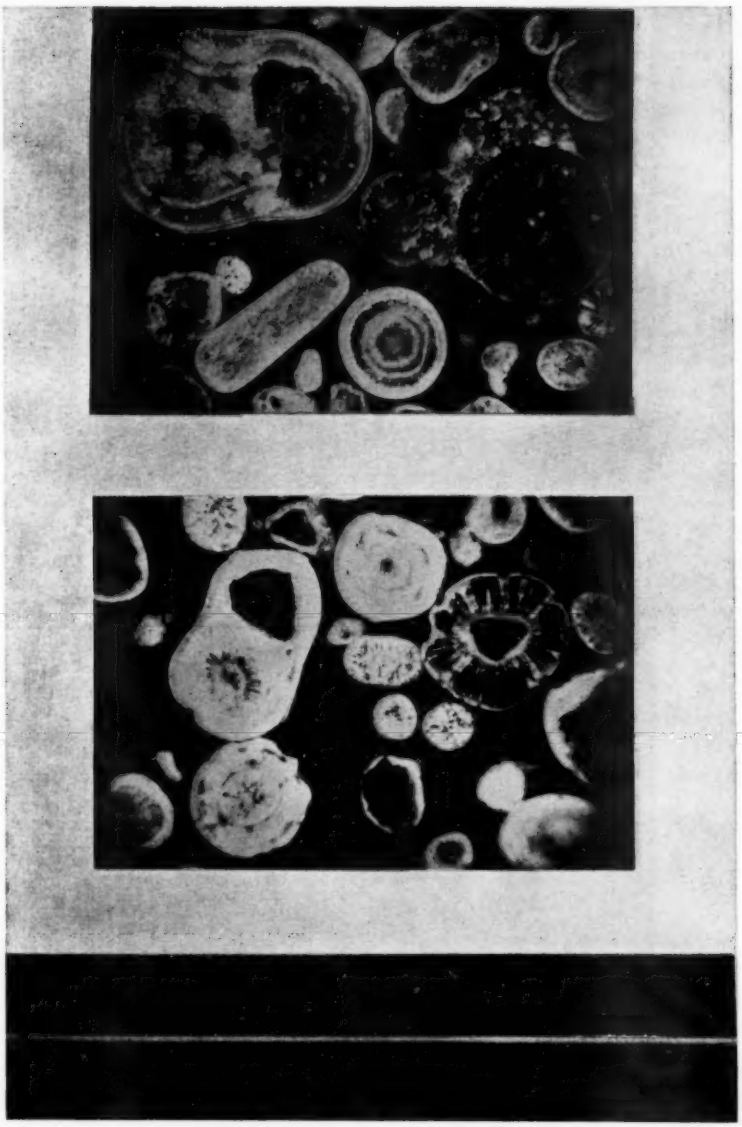
5. Many rods or faecal pellets of the brine shrimp which originally lack any trace of optical continuity are strongly radiate where serving as oölite nuclei (Pls. 9a, 13b).

All these facts indicate a secondary, later origin of the radiating structure. The writer believes that the submicroscopic, outwardly





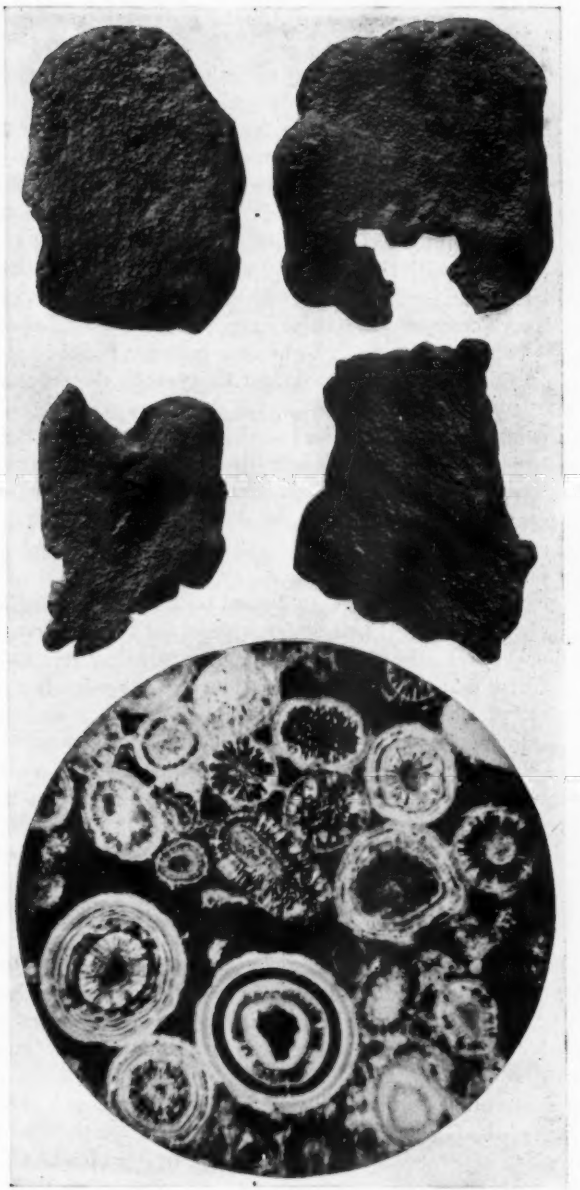
PL. 11a.—Photomicrograph of a group of oölites in transmitted light. Enlarged 60 diameters.
b.—The same as *a* in reflected light.



PL. 12a.—Photomicrograph of oölites, faecal pellets, and groups of both cemented together by new laminae. Enlarged about 35 diameters.

b.—Photomicrograph of thin section of mottled oölites shown in exterior view in Plate 7b. Locality R. Enlarged 35 diameters and photographed in reflected light.

c.—X-ray photograph of white bands of oölites (top) against check sample of aragonite (bottom). By L. S. Ramsdell.



PL. 13a.—Megascopic view of four pieces of "hydrogenic shingle."
b.—Photomicrograph of thin section of shingle showing cemented oölites. Note radial structure of some faecal pellets.

oriented, aragonite crystals revert to the more stable form calcite and in so doing unite, forming much larger crystals, such that they are easily visible under the microscope. The larger crystals are in bundles radiating from the nucleus. The enmeshed clay has either been concentrated along the sides of and between the cone-shaped, radiating, crystal bundles or along the contacts between laminations. The inversion process stimulates aragonite crystals in adjoining bands to invert and merge with those already well developed. The calcite rays or bundles then extend through two or more layers. Unless new concentric layers of cryptocrystalline aragonite with occluded clay are added, the entire oölite tends to become coarsely radial in structure with ghost lines of the former concentric layers as the only evidence of former banding.

In the inversion of aragonite to calcite there is an increase in volume of $8.26 \pm .05$ per cent. The only direction that the expansion can take is outward, thus directing the enlarging calcite crystals to radial orientation. In the faecal pellets the direction of expansion upon inversion is radial although the original submicroscopic aragonite crystals are not known to have any definite orientation.

Where the bundles of crystals extend to the surface a slight bulge is commonly produced (Pl. 10 and 12b), and the clay is segregated in the regions between the bundles, making the inter-ray regions whiter. This indicates that when recrystallization with inversion has reached the surface of the oölite it becomes irregular both in relief and in color, producing the mottled or speckled appearance previously described (Pl. 8). The nature of the surface of the oölites is a reflection of the internal structure. If a new outer layer has been deposited and has not yet developed radial crystals the surface is smooth and pearly white. If crystallization reaches the surface it becomes mottled.

Since the new aragonite-calcite test by Leitmeier and Feigl indicates that some of the rays may be aragonite, the secondary development of radial structure may be due in some oölites to recrystallization without inversion.

The theory of secondary origin of the radiating crystals has been suggested by Twenhofel[76] who examined some oölites from a water boiler which at first were concentric but some months later had evolved a radial structure.

Previous work.—Rothpletz[77] was the first to propose a theory for the origin of the Great Salt Lake oölites. He believed their formation to take place in the gelatinous masses of the algae which he identified

[76] *Op. cit.*, p. 764.

[77] A. Rothpletz, "On the Formation of Oölite," *Bot. Centralb.*, Nr. 35 (1892).

as *Gloeocapsa* and *Gloeotheca* (now known as *Aphanothece Packardii*). From the writer's observations he is certain that if Rothpletz found an algal colony in which even a single oölite grain was embedded, it must be rated as a very rare occurrence. The algae of Great Salt Lake build calcareous tufa-like deposits (pp. 1392–1401) and must have a permanent base for attachment which the shifting and rolling oölites do not afford. The algae are found only as drifting forms here and there in the areas of the oölitic sand.

Seward[78] states that the Great Salt Lake oölites are covered with the cells of *Gloeocapsa* and *Gloeotheca* and that sections of the oölites show these forms to be present in the interiors. The writer was unable to duplicate this observation in any specimen from the entire lake and, therefore, feels that Seward must have dealt with a contaminated sample of oölites.

Mathews' study of the oölites of Great Salt Lake has been referred to. It is believed incorrect in regard to the subaerial growth of the oölites by surface evaporation of capillary water in the production of the concentric laminations; but correct as far as it goes concerning the secondary nature of the radial structure.

A colloidal origin for calcareous oölites in general has been proposed and discussed by several writers.[79] For a summary of the ideas advanced the reader is especially referred to the publication of W. H. Bradley who concludes that some colloid must exist in the water covering the oölites for the formation of concentric laminations. The colloid need not be present in such quantity that the viscosity of the liquid is sufficient to suspend the oölites but only in very small amounts such that the liquidity of the medium is little affected. The colloid is believed to serve as a binding material and is mechanically enmeshed in the acicular crystals of calcite or aragonite. The colloidal binder changes later by coagulation and dehydration to the solid state. The various colloids believed instrumental in forming oölites of various localities and geologic ages are a "nitrogenous organic substance," ferric hydroxide, silica, algal gelatine, or "some of the products of decomposing organic matter so dispersed that they would not increase the viscosity of the solution enough to hold nuclei and small

[78] A. C. Seward, *Fossil Plants*, Vol. 1, pp. 122–23. Cambridge University Press (1898).

[79] Heinrich Schade, "Zur Entstehung der Harnsteine und ähnlicher konzentrische geschichteter Steine organischen und anorganischen Ursprungs," *Zeit. Chemie und Industrie der Kolloide*, Vol. 4 (1909), pp. 263–5.
W. H. Bucher, "On Oölites and Spherulites," *Jour. Geol.*, Vol. 26 (1918), p. 603.
W. H. Bradley, "Algae Reefs and Oölites of the Green River Formation," *U. S. Geol. Survey Prof. Paper 154-G* (1928), pp. 221–22.
W. H. Twenhofel, *Treatise on Sedimentation* (1932), p. 768.

oölite grains suspended." However, the exact mechanics of the participation of such colloids in the building of concentric laminations, as Bradley postulates, is not clear to the writer. As the oölite environment in Great Salt Lake can be ascertained with considerable precision and the processes leading to their growth fairly well deciphered, inorganic precipitation of calcium and magnesium carbonate and a "base exchange" relation between the colloidal clay particles and the aragonite crystals seems the logical theory of origin of the Great Salt Lake oölites. Such a theory may not apply, however, to oölites of other places and times.

SUMMARY

A summary of descriptive facts of the oölites has been given on pages 1371–72. The reader may wish to glance over these pages again before continuing with the following summary of oölite growth.

The precipitation of calcium and magnesium carbonate from the lake brine in the areas of oölite occurrence is the result chiefly of evaporation. The larger particles of carbonate grow at the expense of the smaller or those in the incipient stage of crystallization. Carbonate molecules will deposit directly from solution on the surface of an oölite or some mineral fragment because calcite or aragonite crystallizes readily not only on carbonates but also on most silicate minerals. These carbonate molecules build acicular, submicroscopic crystals of aragonite with dolomite crystals interspersed, all probably oriented normal to the surface of attachment. The Ca^{++} and Mg^{++} ions of the carbonate crystals attract and precipitate clay particles less than 350 microns in diameter from suspension through some process of ionic exchange, forming films or coatings of clay on the exposed crystal faces. The clay thus becomes entrapped along the sides of the growing fibrous crystals. A small amount of organic matter becomes occluded in the same way. Constant agitation by the waves in the troughs of ripple marks exposes all parts of the oölite surface equally to accretion of the carbonate and clay and removes any excess clay that might settle. If it were not for the waves a plastic carbonate clay would probably result. There are alternately periods of slow and rapid accretion which are seasonal. The most rapid growth occurs in the late summer and fall, the time of greatest evaporation. This cyclical variation in rate of growth produces distinct laminations, which because of the clay-coated surfaces of the cryptocrystalline aragonite and dolomite crystals are dense white and nearly opaque.

The development of conspicuous radial structure follows the early formation of the submicroscopic aragonite and dolomite crystals. The aragonite, an unstable form, inverts to calcite when surrounded by

new laminations and removed from the environment of the salt water in which it formed. It may, however, simply recrystallize. With the inversion or recrystallization there is also merging of the crystals until they become visible under the microscope. Certain of the bands invert better or more rapidly than others, thus accentuating the concentric structure. Crystals from one band commonly unite with those of adjacent bands and some radiate through several layers as bundles of fibrous crystals. The dolomite crystals do not invert but probably take part in the merging process. The clay is pushed either to the side of the forming radiate bundles of clear calcite, aragonite, and dolomite crystals, producing dense white inter-ray regions, or to the contacts of laminations. The calcite crystals must grow in radiate structure because the only relief of pressure is outward when the increase of 8.2 per cent in volume, which accompanies the inversion, occurs. Inversion, recrystallization, and merging may extend to such a degree that the whole oölite is radiate with only ghost lines of the former concentric layers remaining.

If the bundles of radiate calcite and dolomite crystals extend to the surface they produce slight irregularities in relief due to their expansion and also a concentration of dense white in the inter-ray areas. A mottled and pitted surface is thus imparted. If a new layer of aragonite crystals and clay has just been added the oölite appears pearly smooth.

The inversion process also proceeds in many brine shrimp faecal pellets after envelopment by the concentric bands. Concentric banding is absent in the pellets. They are of organic origin when viewed as faeces but the radial structure is entirely an inorganic phenomenon.

The limit in size to which an oölite may grow is chiefly a function of wave effectiveness in rolling it about on the lake bottom. The more vigorous the wave activity the larger the particle that can be moved. Another less important factor is the influx of new nuclei for the formation of more oölites which eventually bury the older ones and remove them from wave activity.

HYDROGENIC SHINGLE AND GRANULE SANDS

HYDROGENIC SHINGLE

Several of the beaches of Great Salt Lake are strewn with flat pebbles or cobbles that strikingly resemble shingle. Such material is common along the west shore of Antelope Island, Rozell Point, and especially the southwest shore of Promontory Point north of the Lucin Cut-Off. The southwest shore of Promontory Point has a zone several miles long and fully ½ mile wide fairly well paved with the shingle.

There are no cliffs from which the material could have been eroded, and on examination it is found to consist of oölites cemented together like pieces of sandstone. A few of these flat forms are shown in Plate 13a. In certain locations the cementation is poor and the fragments are friable; in others the bond is good and they are quite firm and hard. Microscopic examination shows the cement to be aragonite or calcite (Pl. 13b) and it must come from the same waters as the $CaCO_3$ of the oölites. The pebbles and cobbles, therefore, can not properly be called clastic shingle because they do not represent flat fragments of previously existing rock, whose edges have subsequently been rounded by wave erosion. The fragments have been built chiefly by precipitation from solution; they are accumulative, not erosional forms. The adjective "hydrogenic"[80] is used to qualify the term "shingle" to distinguish the Great Salt Lake forms from the common shingle of most beaches.

In order that oölites may become cemented together the oölitic sand must remain undisturbed by wave activity for some time. If cementation just begins during a brief interim of quiet water conditions, the next storm will disrupt the bond and normal oölite growth will proceed. If, however, cementation of the surface oölites into a thin crust is thorough enough, the storm may merely break the crust into chips which, persisting through the storm as at times they must do, will strew the storm beach and shallow offshore bottom with the shingle-like fragments. As shown in Plate 13b the fragments range in size from 2 to 6 inches.

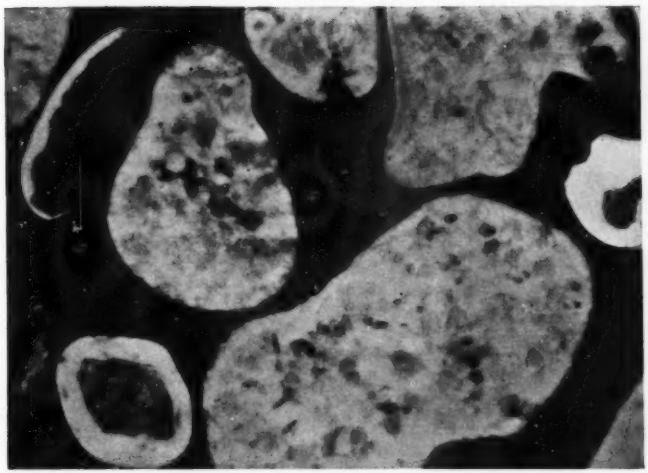
Specimens of hydrogenic shingle taken from Rozell Point do not contain oölites but are composed of numerous mineral grains cemented with $CaCO_3$ in which much clay is occluded. In some specimens the bond is dense and opaque white but in others it is crystalline and only clouded with clay. The mineral fragments range in diameter from 0.04 to 0.15 millimeter. This type of shingle may have formed by cementation of a thin upper crust of clay bottom such as exists in the vicinity of the oil seeps, to be broken up into chips later by storms.

GRANULE SANDS

There is much coarse sand in the storm beaches of Rozell Point (locality B) that must have been derived from wave action on the clay type of hydrogenic shingle. The grains range from 1 to 5 millimeters in diameter, are pearly smooth and rounded and in thin section are the same as the non-oölitic shingle. External and thin-section views of these large sand particles are shown in Plates 14 and 15.

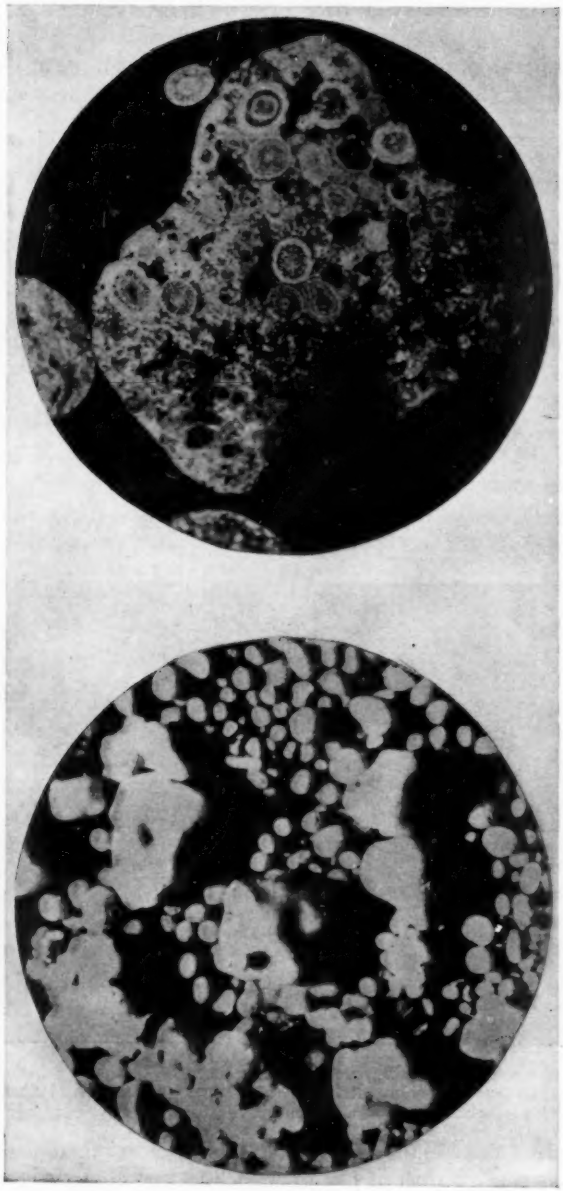
[80] See Grabau, *Principles of Stratigraphy*, p. 283, for classification.

At several localities where oölites were collected, particularly at Black Rock (locality L), very irregular, somewhat nodose, white



PL. 14.—Non-oölitic sand granules. a.—Exterior view, enlarged 25 diameters. b.—Thin-section view in reflected light, enlarged 35 diameters. Much fine white colloidal clay is occluded in carbonate.

grains were found in the sand. Plate 15 is a photomicrograph of these. They generally consist of two to six oölites very firmly covered and cemented together with opaque white $CaCO_3$ and occluded clay. They



PL. 15a.—Thin section of sand granule. Oölites are cemented together in matrix of calcareous material with occluded clay. Locality A. Enlarged 15 diameters.

b.—Exterior view of sand granules among oölites. Granules consist of three or four oölites cemented together by new laminations, same as those of oölites. Enlarged 15 diameters.

PL. 16a.—Salt-crusted algal bioherm, exposed off southwest end of Promontory Point. Looking north.

b.—Fringing bioherm off northeast end of Stansbury Island showing relief of surface.

may have been derived by wave action on some broken algal deposits in which considerable oölitic sand has become cemented. They may also have been formed by wave activity on oölite shingle. In either case after reduction to the small irregular sand particles, they appear to have received additional coatings of calcareous cement.

ALGAL BIOHERMS

DISTRIBUTION

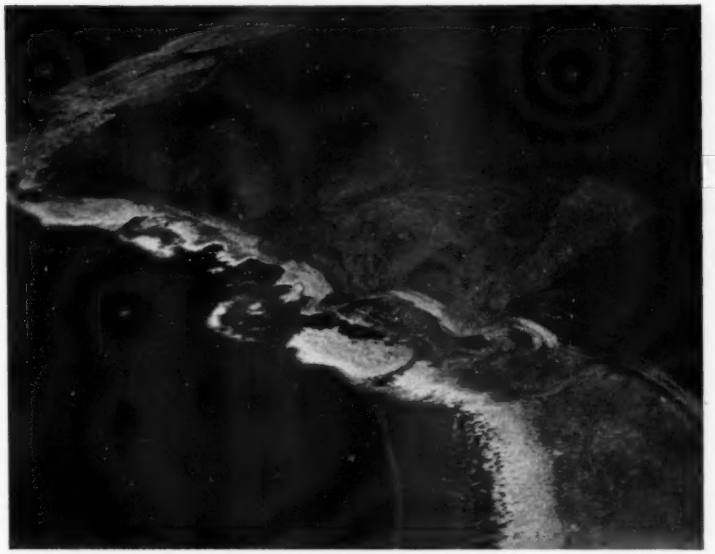
Like the oölites the calcareous deposits principally of algal origin are confined to the shallow-water and shore areas. Their distribution also parallels that of the oölites in that both are limited chiefly to the western part of the lake. The bioherms[81] range in depth from several inches to 10 or 12 feet. The exceedingly low lake level of 1934 exposed wide areas of them, making it possible to photograph large parts of the bioherm surface.

Views in Plates 16, 17, and 18 give some conception of their surface appearance and extensive development. Figure 2 shows with a fair degree of accuracy just how widespread they are and how closely similar their environment must be to that of the oölites. A planimeter calculation from the map indicates their total present area to be 100 square miles. That this extent has varied in past times is shown by borings by J. J. Lilley, engineer from the Diking Project of Great Salt Lake, who struck considerable "tufa" (so-called by lake engineers and boatsmen) at varying depths down to 20 feet, drilling where the lake bottom is now either clay or oölitic sand. None of his borings struck algal deposits in places that would not conform to the present conditions of growth, namely, shallow water, shore-line and wave activity, and aeration. Lilley's borings were all in shallow water between Promontory Point and Fremont Island, and between Fremont Island and Antelope Island, places where several areas of algal bioherms are now located.

DESCRIPTION

Megascopic description.—Megascopically the bioherms are an assembly of flat mounds which merge so closely in most places that no area of the bottom is left uncovered by them. The lines of coalescence are the bottoms of rather sharp, irregularly V-shaped troughs. The relief from bottom of trough to top of mound ranges from 6 to 36 inches; the average relief is about 18 inches. The "trough and mound" character can be seen in the photographs of Plate 16a and b. Nearly all the

[81] The term "bioherm" has been introduced into geologic literature by Cumings and Shrock to signify any calcareous deposit due to colonies of organisms. See Twenhofel, *Principles of Sedimentation* (1932), p. 296.



PL. 17a.—Aerial view of rather precipitous shore line on west side of Promontory Range, showing narrow fringing bioherm.

b.—Aerial view (almost vertical) of fringing bioherm, showing detail of surface. Just south of *a*, west shore of Promontory Range.

mounds are approximately circular and may range from 6 feet to 30 feet in diameter. In some areas where the bottom is not totally covered by the algal deposits, the mounds are small and appear like heads only 1 foot to 2 feet in diameter (Pl. 18a).

Many troughs are filled to a depth of 4–8 inches with loose sand composed of broken-off fragments of the algal bioherms and oölites, most of which have probably been washed in from adjacent areas of oölitic sand bottom.

When viewed from a boat through 2 or 3 feet of water, more than 50 per cent of the mound surface is seen to be covered chiefly with the brown to pink, blue-green, unicellular, colonial alga *Aphanothece Packardii*.[82] Some areas appear to be matted over with a gelatinous film of algal cell secretion, but in others, or here and there on the gelatinous film surface itself, are light brown to pink gelatinous masses 0.5–1.5 inches long, attached at one end, rhythmically waving in the slightly agitated water. Some parts of the surface of the mounds are free from noticeable algal films, but these were probably once covered as they show a striking similarity to those surfaces where the algae are now growing. Considerable travel on and about the shores of the lake has led to the observation and conclusion that the algae must have a firm base of some sort in order to colonize. A loose sand bottom is definitely not favorable, neither is a clay or mud bottom, and it is only in quiet pools within the bioherm areas that algal heads are found on nothing but clay bottom. Any solid body large enough not to be moved by ordinary wave activity may serve as a base for alga attachment, no matter what kind of bottom is present, and from it bioherm growth may proceed and extend radially outward over a considerable area. A piece of oölite shingle, or any other cobble or boulder, may serve the purpose.

On close examination the surface of the algal deposit is generally found to be roughly nodose or knotty, but here and there lamellar and fairly smooth coatings are developed. Plates 18b and 19a, b, and c represent the nodose and Plates 19d and 20b the lamellar.

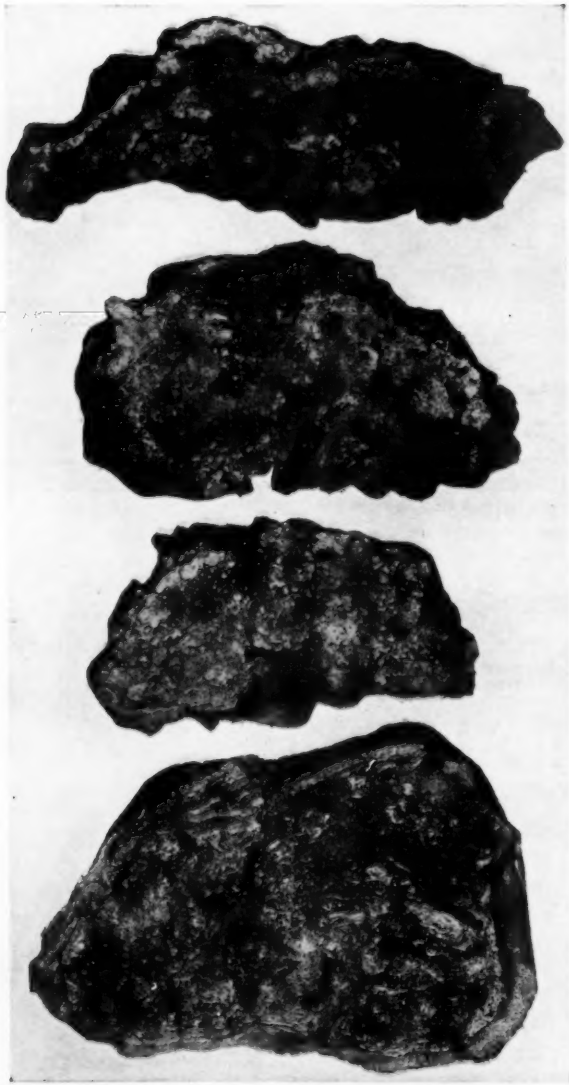
Specimens when taken from the water and allowed to dry are somewhat porous and become friable. In sectioning in the laboratory for megascopic or microscopic observation, it is necessary to impregnate the samples. The porous and somewhat friable nature of the bioherms has led engineers and others familiar with the lake to call the deposits "tufa," but this name is inappropriate because of its implication of spring origin.

[82] See section on Life in Great Salt Lake, pp. 1330 and 1333. The foregoing identification was made by Francis Drouet, University of Missouri.

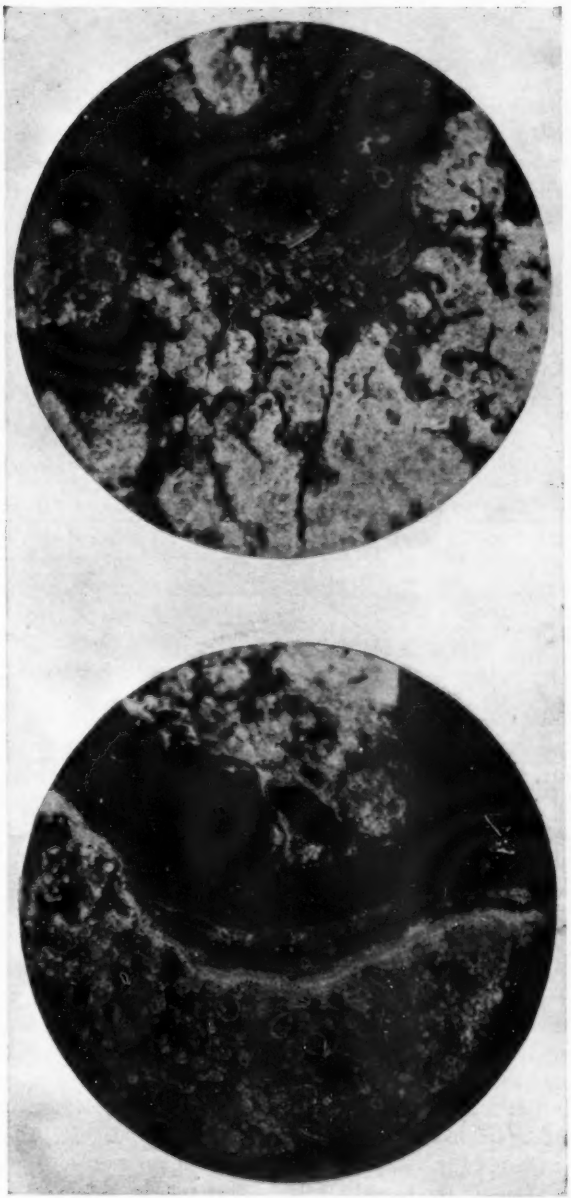
PL. 18.—Views of algal bioherm on northeast end of Stansbury Island.

a.—Peculiar "heads"; top layer is salt foam, next is salt about 3 inches thick, and lower or supporting mass is calcareous algal deposit. Intermediate areas are salt-crusted clay.

b.—Breaking salt crust away and collecting algae and their deposits under it.



PL. 19.—Sectioned hand specimens of algal deposits. Lighter colored, massive, irregular, but crudely banded masses of top three specimens are deposits of *Aphanothece Packardii*. Much of deposit is entrapped fragmental material. Lower specimen is head-like mass composed of concentric layers inclosing friable and chiefly fragmental material. Parts of inclosed mass appear to be algal secretions. Concentric layers were probably formed by *Pleurocapsa entophysaloides* (?). Reduced $\frac{3}{4}$ diameter.



PL. 20a.—Photomicrograph of thin section of algal deposit in reflected light and enlarged 35 diameters. Massive white areas are calcareous deposits of *Aphanothece Packardii*. Various fragmental material including oölites is held between algal layers.

b.—Crust-like deposit of *Pleurocapsa entophysaloides* (?) holding together a mass of oölites and faecal pellets of *Artemia gracilis*. In reflected light and enlarged 35 diameters.

Microscopic description.—Microscopically the bioherms consist of several parts: dense white porous masses (Pl. 20a), dense white lamellar deposits (Pl. 20b), oölites and irregular, calcareous, fragmental material (Pl. 20a and b), and various angular silicate fragments, such as listed in Tables IX and XIV.

TABLE XIX

CHEMICAL ANALYSES OF ALGAL BIOHERMS

Sample	*Per Cent Organic Matter*			*CaO* *MgO*		*Per Cent Clay*	*Per Cent Silt and Sand*
Map Location	N_1	N_2	$\frac{N_1+N_2}{2}\times 14$	*Soluble in Weak Hot HCl*		*Mostly Occluded in Carbonates*	*Mineral Fragments chiefly Eolian Origin*
B	.140	.140	1.97	39.4	3.6	15.2	6.6
U	.105	.105	1.47	*	*	*	*
Ac_1	*	*	*	45.0		14.1	6.0
Ac_2	*	*	*	51.5		6.3	0.1

B. Small algal mound at Rozell Point.
U. Dredging from trough in algae bioherm off Egg Island.
Ac_1. Non-lamellar, porous part of algal bioherm—north end of Stansbury Island.
Ac_2. Lamellar, dense part of algal bioherm—north end of Stansbury Island.
* No analyses made. Organic matter analyses by Parker D. Trask and H. E. Hammar. *CaO* and *MgO* analyses by K. A. Gorton. Clay separations by the writer.

Chemical analysis.—The bioherms contain about 2 per cent organic matter (Table XIX), 77 per cent calcium and magnesium carbonate in the non-lamellar parts, and 20 per cent insoluble material. The $CaO:MgO$ ratio is 11:1. The carbonates were figured on the basis of dolomite ($2MgCO_3 \cdot CaCO_3$ as in clays), and aragonite. No CO_2 analyses were run and hence the presence of excess CaO or MgO is not known. If the high carbonate content is significant as in the oölites, CaO and MgO should be about satisfied with CO_2. On this basis there is 66.4 per cent aragonite and 11.8 per cent dolomite in a representative sample of the algal deposit. The dense lamellar crusts alone analyze about 93 per cent carbonate. The insoluble material consists of three parts: the small angular silicate mineral fragments listed under "silt and sand" in Table XIX, clay particles, and the faecal pellets of *Artemia gracilis*. There is about 6.3 per cent silt and sand and 14.5 per cent clay present in the non-lamellar parts, but in the lamellar, silt and sand are lacking and clay presumably like the clay in the oölites amounts to but 6.3 per cent. A sample of the loose sand in the troughs or lanes between the mounds was found to contain 1.47 ± per cent organic matter, slightly less than that of the algal deposits, proper.

It is interesting to compare the ratios of occluded clay to total carbonate (acid-soluble basis) in the oölites and in the lamellar parts of the algal deposits. They are closely similar and are as follows:

$$\text{oölites} - \frac{\text{clay}}{\text{carbonate}} = \frac{1}{15.6}$$

$$\text{Lamellar algae deposit} - \frac{\text{clay}}{\text{carbonate}} = \frac{1}{14.9}$$

The alga ratio is based on one analysis and is, therefore, not as representative as the oölite ratio which is based on a number of analyses.

ORIGIN

Much has been written about the origin of calcareous algal deposits. Those of Great Salt Lake are found in shallow water and near shore where wave activity and subsequent circulation is strong, but must have a permanent base for attachment. This much of the origin is clear from the foregoing descriptions but the manner of carbonate precipitation remains to be discussed.

Ocean, lake, and river algae deposit calcium carbonate in different ways. According to Twenhofel

> In *Lithothamnium* the precipitate forms crusts over the surfaces on which the plant grows; the precipitate in *Halimeda* is a sieve-like cover about the tips of the algal filaments; and in *Acertularia* a tube is formed about the stalk of the plant. In *Chara* and the corallines the lime is deposited in the cells and cells walls of certain parts of the plants.[83]

Black, in the study of the algal sediments of Andros Island,[84] finds that the algae, chiefly *Schizothrix*, *Symploca*, and *Phormidium*, have filaments enclosed in a mucilaginous sheath to which mineral particles adhere. If the sediment in suspension is very fine-grained, the mucilaginous sheaths entrap an appreciable quantity, and appear to do this selectively. Thus if a mixture of clay, silt, and sand is drifted over the algal heads at a velocity sufficient to keep the sand grains moving, the clay particles cling to the mucilage of the filaments but very little sand is retained. The calcium carbonate which is part of the entrapped clay is not necessarily precipitated by the algae. The deposits are entirely unlithified.

Knowledge of the manner of carbonate and clay precipitation of the filamentous types is of no great help in studying the algae of

[83] W. H. Twenhofel, *op. cit.*, pp. 306–11.

[84] Maurice Black, "The Algal Sediments of Andros Island, Bahamas," *Phil. Trans. Royal Soc. London*, Ser. B, Vol. 222 (1933), pp. 165–92.

Great Salt Lake where only the unicellular are important bioherm builders. Of the unicellular algae in Great Salt Lake *Aphanothece Packardii* is by far the most important; in fact, so negligible are the rest that, if it were not for the interest that the exceptions or variations arouse, they would not need to be considered. The characteristic mound type of deposit as previously described and as illustrated in Plates 16, 17, and 18 is of this species. Its surface is nodose, consisting of many small protuberances as in *a*, *b*, and *c*, Plate 19. When hand specimens are sectioned they are found to consist of firm and dense white crusts between which is a somewhat friable fragmental material. This is made up of fragmental algal deposits, oölites, shrimp faecal pellets, and some silt and clay. Plate 20 illustrates the nature of the dense white material for which the alga is directly responsible. The fragmental material has been crusted in by the algal laminations.

Here and there is found a laminated head or a group of heads, each 4 to 16 inches in diameter. Only one sample was found in which living algae occurred and these proved to be *Pleurocapsa entophysaloides* (see section on life in Great Salt Lake, pp. 1332, 1333). Plate 19d is a megascopic view of these layers and Plate 20b shows strikingly the encrusting ability of this species.

No microscopic diagnostic marks other than the massive irregular nature of the crusts of *Aphanothece Packardii* and the smoother laminated crusts of *Pleurocapsa entophysaloides* were detected.

The *Aphanothece* live in pink, green, and brown colonies of gel some of which are firmly attached, covering as a slime or mat small areas but leaving intervening rock surfaces bare. Commonly, they are loosely anchored at one point, waving back and forth in the moving water. Some become detached, probably during storms, and float and drift on the lake surface.

The *Pleurocapsa* as far as observed live in thin jelly mats entirely covering the areas that they occupy, and therefore their deposits are more regular and tabular.

That the algae extract carbon dioxide from the water during photosynthesis and that this is the cause of calcium and magnesium carbonate precipitation is generally agreed. It seems certain that the carbonate does not fall as a marl around the colonies of algae because it is directly under the mat of gel that the crust forms and it is definitely hard and not plastic. It would appear, although there is no experimental proof, that the carbonate molecules as well as the fine colloidal clay pass through the gel of the algal colonies and are laid down as a crust, nodular in the case of *Aphanothece* and tabular or lamellar in the case of *Pleurocapsa*. Silt or sand particles that settle

upon them probably do not pass through the gel and are not incorporated in the lamellar crusts.

No evidence could be found of fossilization or preservation in any way of the unicellular algae. The deposits are not diagnostic and, therefore, can be used only in the broadest way in the identification of species.

The presence or abundance of bacteria on the bioherm surface and the rôle they play in carbonate precipitation can only be conjectured at the present time. ZoBell and Smith[85] have begun a study of the lake's bacteria and in personal communication ZoBell says,

> Most of the bacteria are periphytes which grow only when attached to some solid surface. This characteristic has a tendency to localize their activities . . . The organic matter (in the water) is converted into ammonia and CO_2 as end products. The pH of the water is just at the borderline for $CaCO_3$ precipitation so very minute increases in alkalinity in localized areas could start it.

It would appear, then, that the periphytic bacteria are just such microscopic organisms as would assist prominently in building the bioherms of Great Salt Lake. Their rôle, although definitely suspected as important, must await the further research of the bacteriologist.

FAECAL PELLETS

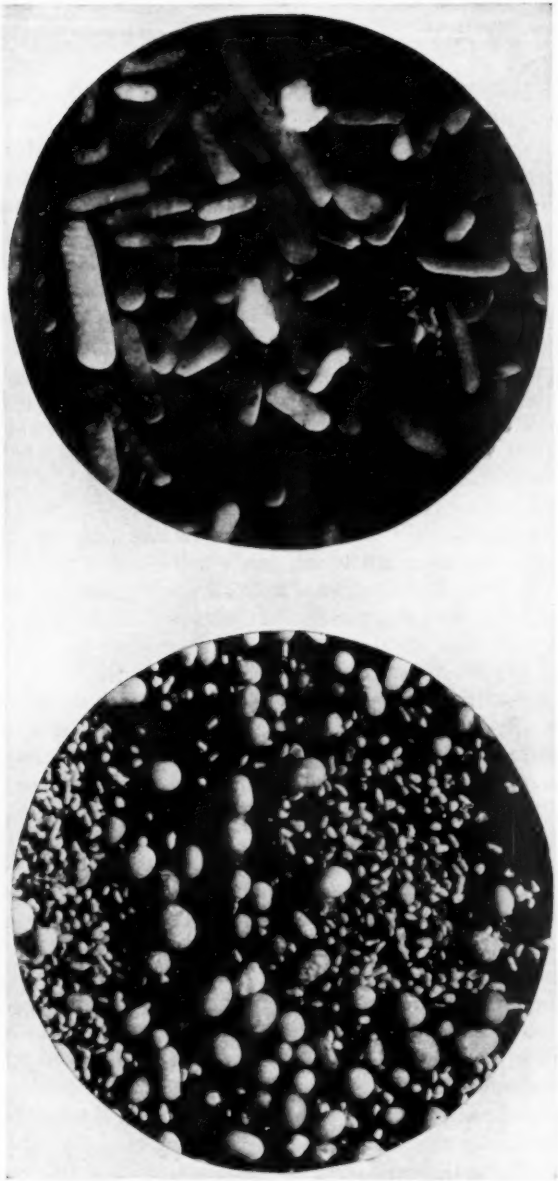
Small rod-shaped bodies are very common in the sediments of the lake. Although they are not the same in shape as the spherical oölites they still have similar compositional and in part structural features. They are the faeces of the brine shrimp, *Artemia gracilis*.

DESCRIPTION

Some of the faecal pellets are enclosed in thin concentric bands which still reflect clearly the rod-shaped form of the nucleus pellet. In most samples examined, however, the concentric bands are absent or only abortively developed. The concentric layers where present are in every respect comparable to those of the spherical oölites and their mode of formation must be the same. The pellet is of bacilli-like form, and in the longer specimens strikingly cylindrical and symmetrical. In the shorter forms some irregularity is noted but in all there can be no mistaking the rod-like shape. The photomicrographs of Plates 9b and c, 21, and 22 show various aspects of the pellets both externally and in cross section.

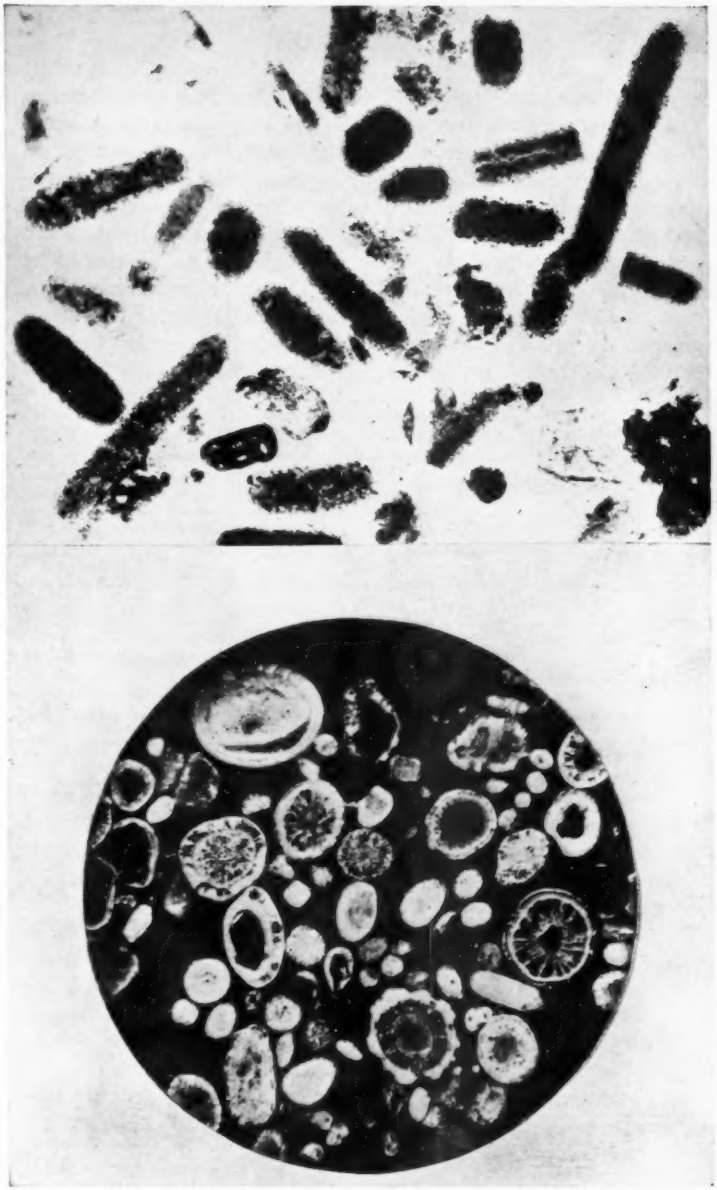
The rods have been observed in two sizes which are distinguished by the names "long rods" and "stubby rods." The stubby rods are

[85] C. E. ZoBell, D. Q. Anderson, and W. W. Smith, *op. cit.*, pp. 253–62.



Pl. 21a.—Photomicrograph of faecal pellets of brine shrimp, *Artemia gracilis*, from locality F. Enlarged 35 times.

b.—Oölites together with faecal pellets from locality K. Pellets are somewhat broken and rounded due to wave activity. Enlarged 15 times.



PL. 22a.—Photomicrograph in transmitted light of faecal pellets of *Artemia gracilis* after solution of carbonate with *HCl*. Remaining clay mesh is mostly opaque. Locality F. Enlarged 60 diameters.

b.—Thin section of oölites and faecal pellets from locality K, same as those shown in exterior view in Plate 8b. Note tendency toward radial crystallization of nuclear faecal pellets. Enlarged 35 diameters.

associated chiefly with the oölites and the long rods with the clays Transitional sizes are very common. The long rods range in length from 0.3 to 1.0 millimeter, the average length being about 0.50 millimeter. They have a diameter of about 0.1 millimeter. The stubby rods range in length from 0.05 to 0.32 millimeter, the average length being 0.20 millimeter.[86] It is believed that the agitation by the waves wears down the ends of the pellets, although they are generally firm, resembling in this respect the oölites. The cryptocrystalline ground mass as viewed in thin section under the petrographic microscope suggests recrystallization from the extremely fine, precipitated particles of $CaCO_3$ and, perhaps, accounts for the firmness of the rods.

TABLE XX

CHEMICAL ANALYSES OF FAECAL PELLETS

Sample	*Per Cent Organic Matter*			*CaO* *MgO*		*Per Cent Clay*	*Mineral Fragments*
Map Location	N_1	N_2	$\frac{N_1+N_2}{2}\times 14$	*Soluble in Weak Hot HCl*		*Occluded in Bands and Nuclei*	*Held partly in Rod-Shaped Nuclei*
F_1				40.6	3.2	17.3	5.3
F_2	.065	.060	.87	38.1	2.9		
Average	.065	.060	.87	34.4	3.05	17.3	5.3

Organic analysis by H. E. Hammar. *CaO* and *MgO* analyses by K. A. Gorton, University of Michigan. The latter also assisted in the clay and mineral fragment separation. Both samples were clean rods with a few small spherical oölites, free from external clay or mineral fragments. F_1 consisted of light gray pellets and F_2 of dark gray

When surrounded by lamellar layers, thus becoming the nuclei of the oölites, many develop strong radial structure. This is a secondary process, entirely physico-chemical and similar to that of the radial structure of the laminations of the oölites, previously described and explained (Pls. 9c and 22).

The pellets are white or stained faintly tan when viewed in reflected light but when observed in transmitted light appear cloudy with many dark specks but cryptocrystalline for the most part. Under high magnification the dark specks prove to be minute mineral fragments while the cloudiness is due to occluded white clay in a dense crystalline groundmass of calcium and magnesium carbonate.

As indicated by chemical analysis (Table XX) the pellets consist of calcium and magnesium carbonate, occluded, fine, white clay, and very small mineral fragments.

[86] Rubey of the U. S. Geological Survey calls the writer's attention to the similar "pellet beds" in the Overton magnesite, *U. S. Geol. Survey Bull. 871*, p. 129, and Pls 11 and 12.

When the carbonate part of the pellet is dissolved out with hydrochloric acid, there remains intact a body of the same shape and volume as formerly, as if the tiny mineral particles were held together in a clay mesh or network. The carbonate-free pellets are shown in photograph a, Plate 22.

DISTRIBUTION

All lake samples examined, no matter whether clays, oölites, or bioherms, contained pellets. They are found in the eastern part of the lake as well as in the western, in deep water as well as in shallow.

The Promontory Point area, particularly in the vicinity of the boat pier (locality F), is one of extensive pellet development. There are, at least, 1,000 acres of either pure pellet sand or black mucky material with abundant pellet content, and the area may be much larger. Its extent was only roughly estimated from examination along the shore and out to maximum wading depth. The sand is at least 2 feet deep and ripple marks and shallow bars are common. There is a concentration of pellets, almost to the exclusion of all other material, of 1 or 2 million tons and possibly several times this much. No other area is believed to exist where such a concentration prevails. From the table of the petrographic analyses of the lake sediments (Table IX) an average of the pellet content of all sediment samples, giving each sample equal areal weight, was 31 per cent. The pellets must be recognized, then, as one of the most important parts of the sediments in the lake.

ORIGIN

A microscopic study of the brine shrimp reveals the mechanism of the formation of the pellets. They are formed in the intestine of the long caudal appendage. Of the digestive system of the brine shrimp Jensen[87] states.

> The oesophagus is short and leads to the stomach, which is situated in the head . . . The intestine is a straight tube. The division extending through the thorax is twice as large as that passing through the abdomen. The intestine includes a well marked rectum, which is provided with constricting circular muscles.

The white opaque clay and carbonate may be seen gathering in the thoracic region and condensing into a regular cylindrical rod extending down and filling the intestine in the abdomen. This feature is illustrated in the photographs of Plate 23. The constricting circular muscles of the rectum divide the continuously forming contents of the intestine into separate pellets in the process of discharging. The

[87] A. C. Jensen, "Some Observations on *Artemia gracilis*, the Brine Shrimp of Great Salt Lake," *Biol. Bull.*, Vol. 34 (1918), p. 19.

composition of the faeces indicates that the shrimp takes in a great deal of inorganic matter with its food. Jensen's conclusion can not be true that they feed entirely on algae or their gelatinous secretions.[88] Various bacteria[89] and protozoa inhabit the lake water and the bottom clays (pp. 1330–33). If the shrimp is a bottom scavenger, it is easy to understand the presence of so much inorganic material in the digestive tract. However, brine shrimps are reported by salt workers[90] to clarify brine solutions. In the shrimp's quest for suspended food in the water it must devour both mineral and organic particles without much discrimination. Baas-Becking[91] has experimented with the brine shrimp by placing it in suspensions of barium sulphate, calcium carbonate, and calcium sulphate. He states that the liquid with its mineral particles passed through the digestive tracts where the particles are coagulated into small pellets. Five artemiae cleared 100 cubic centimeters of milky barium sulphate suspension in 24 hours.

Since the pellets contain 77 per cent carbonate and the bottom clays average only 47 per cent, the shrimps, if bottom scavengers, must selectively ingest a proportionally large part of carbonate. This is difficult to account for. On the other hand, if near surface swimmers as commonly observed, their chief mineral consumption should be fine dust particles settled from the atmosphere, and colloidal clay and aragonite crystals. Again it seems peculiar that the carbonate content of the pellets should be as high as 77 per cent. It may be that carbonate is precipitated within the intestinal tract, or that the food material varies from season to season, that is, during the summer season of heavy carbonate precipitation an extra large amount of carbonate crystals is ingested. Unfortunately the exact origin of the brine shrimp's food must be left in doubt until further work is done.

E. R. Edge has recently studied various arthropod faecal pellets[92] and has found in general that they are rod-like, of varying lengths, with a definite circular cross section. He noted that not only the amount but also the kind of food in the intestine at the time the pellet was formed influenced its shape. The size of the animal also had a direct influence on the size of the pellet. The brine shrimp pellets

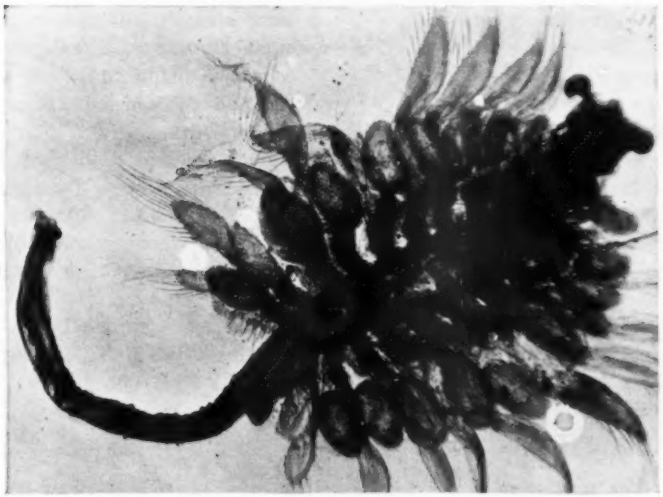
[88] *Op. cit.*, p. 23.

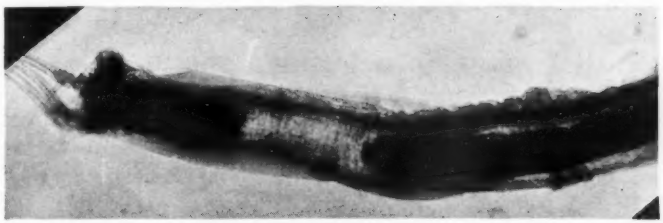
[89] C. E. ZoBell, D. Q. Anderson, and W. W. Smith, *op. cit.*, pp. 253–62.

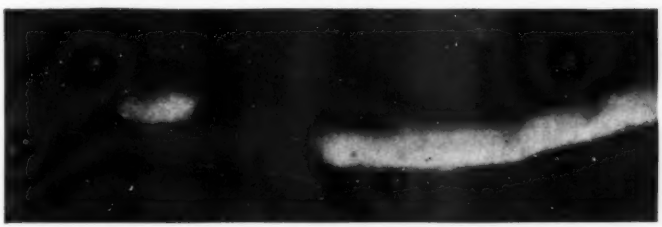
[90] L. G. M. Baas-Becking, "Historical Notes on Salt and Salt Manufacture," *Scientific Monthly*, Vol. 32, No. 5 (1931), p. 445.

[91] *Ibid.*, p. 445.

[92] E. R. Edge, "Faecal Pellets of Some Marine Invertebrates," *Amer. Midland Nat.*, Vol. 15, No. 1 (1934), pp. 83–84.







PL. 23a.—Photomicrograph of female brine shrimp, *Artemia gracilis*. Enlarged 17 diameters.

b.—Enlargement of caudal-like abdominal appendage. Intestinal contents appear opaque in transmitted light. Enlarged 60 diameters.

c.—Same as *b* but photographed in reflected light.

agree very closely with these size and shape observations, that is, the rod-like shape with circular cross section and the varying size depending on the size of the shrimp. Edge's marine arthropods were all larger than *Artemia gracilis* and hence his pellet dimensions are considerably larger but, in proportion, quite comparable.

The shrimps have been observed in great numbers in all parts of the lake by the writer as well as several other authors. Talmage[93] believes them to be most abundant between the months of May and October. Jensen[94] believes they die off in the winter, passing that season in the egg stage but Talmage in the above reference reports collecting them in mid-winter at a temperature below 0°C. So much of the bottom clays have passed through the intestinal tracts of the shrimps that, as previously shown, about one-third of the lake sediments are faecal pellets. The pellets found in the oölite zone are generally stubby, only here and there a long one being observed.

LATERAL SEDIMENTARY VARIATIONS AND BURIAL OF ISLANDS

The relation of the various types of sediments of Great Salt Lake is of interest and two cross sections have been prepared (Fig. 7) that represent the most characteristic lateral variations and, as far as known, the vertical structure.

LATERAL VARIATIONS

Within a surprisingly short distance, particularly around the islands, the coarser clastics of alluvial fans reaching in many places to the water's edge are supplanted by calcareous and argillaceous loams, clays, and oozes. In places algal bioherms separate the coarser clastics from the calcareous clays. Other lateral variations are shown on the cross sections.

The dip of the surface of the alluvial fans is the initial dip of the porous sand, gravel, and boulder lenses that constitute the fans. The dip ranges from 2° on the outer slope to 12° on the upper slope. Alluvial fan material is very porous, especially the coarse lenses many of which are artesian aquifers. The initial dip of the calcareous clays and loams of the lake bottom is 5 feet per mile or less.

BURIAL OF ISLANDS

The islands of Great Salt Lake are in all stages of burial by their own subaerial debris and by the lake sediments. Some are very large and high, such as Antelope and Stansbury islands (Pls. 1a, 2a, and 3b) and not in any immediate danger of complete sedimentary burial.

[93] J. E. Talmage, *op. cit.*, p. 67.

[94] *Op. cit.*, p. 24.

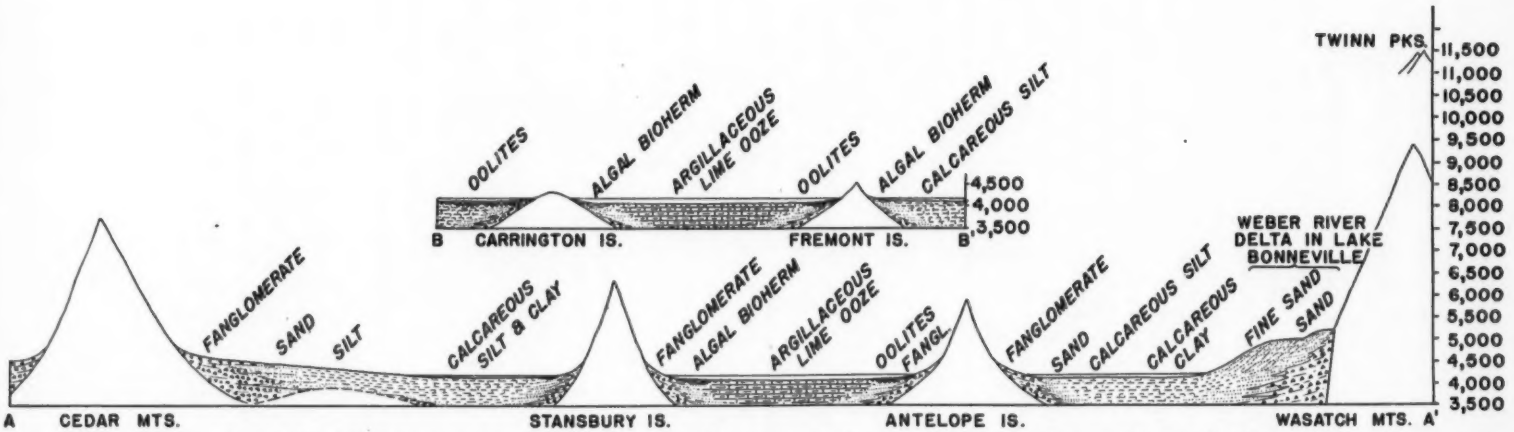


FIG. 7.—Sections along *AA'* and *BB'* showing arrangement of valley and lake sediments in Great Salt Lake Basin and approaching burial of islands of Paleozoic and pre-Cambrian rock by Pleistocene and Recent sediments. Vertical scale is grossly exaggerated (20 to 1) in order to show detail in sedimentary layers.

Others are somewhat small and low, such as Fremont and Carrington islands (Pls. 1a and b, and 3a) and are approaching rapidly the time when complete burial will occur. Only the uppermost peaks of others show through the lake sediments. Gunnison and Bird islands (Pl. 1a) are examples. Others are most probably completely buried. Continuations of the mountain ranges seem to be the most likely trends where buried islands may be found.

Rate of burial.—The rate of calcium carbonate accumulation has already been computed (p. 1332, and Table VII). The lake sediments are not entirely carbonate, however, and therefore the clastic content must be considered. This increases the total figure considerably. The presence of *Ca* in several chemical precipitates in the lake (p. 1357) makes it difficult to determine the amount of "$CaCO_3$" precipitated when stated without reference to the minerals in which the *Ca* occurs. Some *Ca* is also absorbed in base exchange relationship. The three groups of clays average 18 per cent aragonite, 5 per cent dolomite and 0.6 per cent absorbed Ca^{++}. The total *Ca*, therefore, when combined with CO_3 is about 21 per cent. In the algal deposits there is about 70 per cent $CaCO_3$ and in the oölites about 84 per cent (see Tables XV and XIX). The clays cover about 70 per cent of the lake bottom, the oölites about 20 per cent and bioherms about 10 per cent. When averaged on this basis the result is 38 per cent calcium carbonate. Therefore, the total rate of sediment accumulation is over twice that of calcium carbonate deposition. The thickness of the total annual increment has been determined for various degrees of compaction and is shown in Table VII.

If the sediments are compacted so as to have a water content of 30 per cent, the rate of accumulation is about 12 feet in 10,000 years. At this rate it would take some 1,250,000 years to bury Antelope Island. Carrington Island, which is about 60 feet high, would be buried in about 50,000 years. However, it seems unlikely that the climate will remain constant for any such length of time, or that the area will be free from further faulting of the still active Basin and Range orogeny. The figure arrived at for the rate of sedimentation may be assumed to be closely related to the rate of erosion of the surrounding mountain areas.

Buried hill structure.—In Kansas and Oklahoma oil structures are known in which a series of gently arched strata rest uncomfortably on granite hills or older folded sedimentary rocks, completely burying them. They were first recognized by Blackwelder[96] and named "re-

[96] Eliot Blackwelder, "The Origin of Central Kansas Oil Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 4 (1920), pp. 89–94.

flected buried hills" by Powers.[96] Initial dips about such buried hills have been described by Bridge and Dake,[97] thus accounting for structure along the side of the relief feature. After complete burial by material coming from adjacent highlands, differential compaction of the clay above and around the hill occurs and the shape of the hill is reflected in the structure of the overlying strata. Nevin,[98] Monnett,[99] Hedberg,[100] and others have made valuable contributions to this subject.

From reference to Figure 7 and Plates 1, 2, and 3, it is clear that definite anticlinal structures are in the process of building or have already been built in the basin of Great Salt Lake. The lenses of the alluvial fans dip away from the mountain from which the material was derived. They are porous and lithify chiefly by cementation. The calcareous and argillaceous lake sediments are laid down nearly horizontally but dehydrate and compact (pp. 1339 and 1341), thus accentuating the structure.

The subaerial deposits around the islands become finer and less extensive as burial proceeds, and with complete burial only the typical fine, smooth, loams and clays will extend over the island.

If the lake clays become a source rock of petroleum in the future, as seems probable, the structure, the reservoir rock, and the cap rock are apparently provided and a set of conditions highly favorable for oil migration and accumulation will exist.

[96] Sidney Powers, "Reflected Buried Hills and Their Importance in Petroleum Geology," *Econ. Geol.*, Vol. 17 (1922), pp. 233–59.

[97] I. Bridge and L. L. Dake, "Initial Dips Peripheral to Resurrected Buried Hills," *Missouri Bur. Geol. and Min. Biennial Rept.* (1928), Appendix 1, pp. 1–7.

[98] C. M. Nevin and R. E. Sherrill, "Studies in Differential Compaction," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 1–22.

[99] V. E. Monnett, "Possible Origin of Some of the Structures of the Mid-Continent Oil Field," *Econ. Geol.*, Vol. 17 (1922), pp. 194–200.

[100] Hollis Hedberg, "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 1035–72.

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DARROW SALT DOME, ASCENSION PARISH, LOUISIANA[1]

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ABSTRACT

The Darrow salt dome is located on the east bank of the Mississippi River between Baton Rouge and New Orleans, 30 miles southeast by road from Baton Rouge and 75 miles northwest from New Orleans. It is the first salt dome east of the Mississippi River on which oil in sustained commercial quantities has been produced. The first producer was completed in March, 1933, and on December 31, 1937, the field had a daily production of 2,074 barrels from eight wells, with a total production of 1,518,921 barrels through that date. The proved area at the end of 1937 was about 40 acres, as determined by data from the thirty wells drilled, of which eleven produced oil in some quantity.

Production on the dome has been obtained from super-cap sands and from flank sands, both of which probably represent the same Miocene horizon. A small amount of oil was produced from sands above the cap rock, but the most important production has been secured from what appears to be the same paleontologic horizon faulted to the 5,700-foot and 7,000-foot levels.

The highest part of the dome is 4,627 feet below the surface. At the 6,000-foot contour the salt mass is practically circular in plan with a diameter of 4,800 feet based on present data.

The usual difficulties attendant on pioneer development of piercement-type domes have been experienced in operations at Darrow, among them being the problem of locating the very narrow productive zones, the faulting which has interrupted the peripheral continuity of these sands, and the lack of recognizable datum beds above the oil sands.

The deepest well on the dome was abandoned dry at 7,980 feet in shale of Oligocene age, which is the oldest geologic formation reached on the structure to date.

INTRODUCTION

Geographically, the Darrow salt dome is located in Ascension Parish, Louisiana, on the east bank of the Mississippi River, with part of the dome underlying the river itself. The structure is readily accessible by improved highways from Baton Rouge and New Orleans. It is about 30 miles by road from Baton Rouge and 75 miles from New Orleans. Considerable interest has been taken in this dome because it has been the only one east of the Mississippi River on which appreciable production has been sustained for several years, although it was not the first one east of the river to produce oil. The dome is situated 3 miles north of the town of Darrow, from which it derives its name.

Geologically, the dome is located very close to the eastern edge of the Gulf Coast salt-dome basin. For many years, as the coastal salt-dome area was extended eastward, the Mississippi River was popularly considered as the ultimate boundary between the definitely

[1] Read before the Association at New Orleans, March 17, 1938, by permission of the Humble Oil and Refining Company. Manuscript received, June 18, 1938.

[2] Geologist, Humble Oil and Refining Company, 2307 American Bank Building.

potential producing area on the southwest and the region of questionable possibilities on the north and east. Intensive exploration work during the last few years has failed to extend the producing area appreciably eastward from the actual channel of the stream, so that the popular conception of the Mississippi River as the approximate physical boundary between the producing and non-producing areas has been justifiable to a large degree.

Acknowledgments.—Acknowledgment is made to the Humble Oil and Refining Company for permission to present this paper, and to those associates in the company who have contributed helpful comments during its preparation. The writer is indebted to T. I. Harkins[3] for permission to use information contained in his unpublished paper on the Darrow dome, and to Henry V. Howe[4] for constructive paleontologic criticism.

HISTORY

A reported oil showing in a water well attracted the attention of the Gulf Refining Company and Union Sulphur Company in 1927, at which time the former company placed a torsion balance in the area and located an anomaly centering under the Mississippi River. The refraction seismograph was used without success to determine definitely the location of the dome. In 1929, the newly developed reflection seismograph technique was used on the area by a Geophysical Research Corporation crew under T. I. Harkins. Considerable difficulty was experienced in getting reflections through the weathered layer forming the natural levee of the Mississippi River, so that a variation of the usual method was worked out satisfactorily on the shallow beds of the area. This method, which subsequently became known as dip-shooting, successfully delineated the dome as proved by subsequent drilling.[5]

The Gulf Refining Company drilled one of the three early dry holes in the area before the dome was definitely located by reflection seismograph. In 1932, following this work, the Gulf Refining Company sub-leased the entire dome to the Rio Bravo Oil Company, and in September of the same year, the latter company completed its first well, Community No. 1, as a producer from super-cap sands at 4,008–37 feet at the rate of 2,400 barrels of pipe-line oil per day.

[3] T. I. Harkins, "Geophysical History of the Darrow Dome." Read before the American Association of Petroleum Geologists at Tulsa, Oklahoma, March, 1936, but not yet published.

[4] Henry V. Howe, director, School of Geology, Louisiana State University; director, Research Division, Louisiana Geological Survey.

[5] T. I. Harkins, *op. cit.*

Subsequently, this well failed to produce and was drilled into salt from 4,627 to 4,903 feet, later being reworked to make a small pumper from the original sand. The Rio Bravo Oil Company drilled two other wells into salt on the dome, but as neither of these wells was productive, the dome was surrendered to the Gulf Refining Company in 1933. The Gulf Refining Company drilled a dry hole into salt in December, 1933, and sub-leased the dome to Turnbull and Irwin. The latter organization drilled one well as a dry hole in March, 1934, and sub-leased the dome to the Humble Oil and Refining Company in July of the same year.

The first well drilled by the Humble Oil and Refining Company was located on the southwest flank of the dome, considerably farther from the center than any previous test. This well, Gumbel No. 2, was completed in February, 1935, as a successful producer from 30 feet of oil section, the top of which was encountered at 5,751 feet. This well showed a potential of more than 1,000 barrels per day on $\frac{3}{8}$-inch choke and with a low gas-oil ratio. In line with good production practice, this well was choked to a small portion of its potential production and has flowed continuously for more than 3 years with little change in pressures or oil-gas ratios. Subsequent efforts to extend production from this well resulted in repeated failures until eight dry holes had been drilled.

After production had been established on the southwest flank, an equally successful attempt was made on the east flank where Community No. 5 was completed in about the same zone as the Gumbel No. 2. From the Community No. 5 the producing zone was extended, more or less successfully, for several locations north and southwest around the periphery of the dome at about the same depth, though it was found that the oil-bearing area was very restricted in width, and faulted or lensed out at several locations along the normal trend.

In June, 1937, a new and deeper producing area was opened on the southwest flank when V. Landry No. 1 was completed from an oil sand encountered at 6,985 feet, marking an appreciable addition to the reserves estimated for the dome. Since discovery of the deeper sand, several wells have been completed from this horizon.

PHYSIOGRAPHY

Located at the edge of the Mississippi River, the dome underlies the broad natural levee which slopes gently for 1 mile from an elevation of 25 feet at the river to 15 feet at the edge of the swamp. Although there is no indication of uplift in the topography, or in the

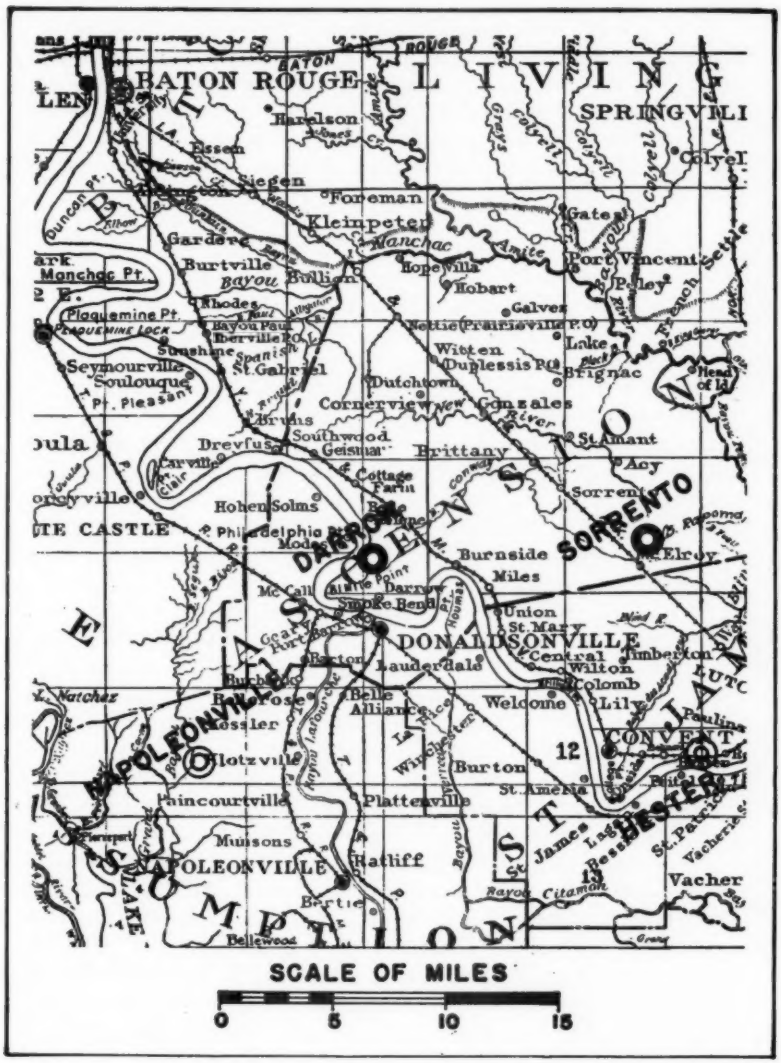

FIG. 1.—Map showing location of Darrow dome and its relation to surrounding area.

surface materials, there is a suggestion of recent upward movement in the position and shape of the large horse-shoe meander of the river. The stream appears to have been deflected from its normal southeast course although, because it is aggrading, the juxtaposition of structure and stream pattern may be mere coincidence. The western edge of the dome may extend beneath the present batture to the actual stream channel. The eastern edge underlies a small portion of the cypress swamp.

GEOLOGY

General description.—The dome, itself, is of the normal piercement type common to the Louisiana-Texas Coastal Plain with no particularly marked characteristics to make it outstanding in its class. Dome material reaches to within 4,627 feet of the surface over the gently rounded top of the salt mass which, at the 6,000-foot contour, is essentially circular in plan with a diameter of about 4,800 feet. The salt exhibits some flattening on the south shoulder of the dome slightly below the 6,000-foot contour, though this is thought to be limited to the south flank of the structure. There has not been sufficient drilling to determine the shape of the salt mass on all sides, but, so far, there seems no reason to suspect appreciable salt overhang in the areas actively being explored.

Cap rock.—Because operations over the central portion of the dome have been unsatisfactory from the standpoint of production, few tests have been drilled over the top of the structure, and information as to the amount and extent of the cap rock is very limited. The maximum amount of true cap rock found anywhere on the dome is 61 feet, of which 37 feet is limestone and the remaining 24 feet anhydrite. Over this true cap rock a thin section of mineralized sedimentary rocks is present, and nearly all sands and shales immediately adjacent to the salt are heavily indurated with calcite.

Faulting.—In common with other domes of this type, considerable faulting occurs on the flanks and probably over the top due to tension and differential drag of the strata. These faults are both radial and tangential, and, because of the lack of recognizable key beds, are difficult to interpret with any great degree of confidence. The breaks in the trend of production of the shallow sand have been most troublesome, and appear to a large extent to be due to radial faulting. Paleontologic data suggest that all production on the dome has been obtained from the same stratigraphic horizon, so that peripheral faults are responsible for displacement in the position of the oil section producing at three levels on the dome.

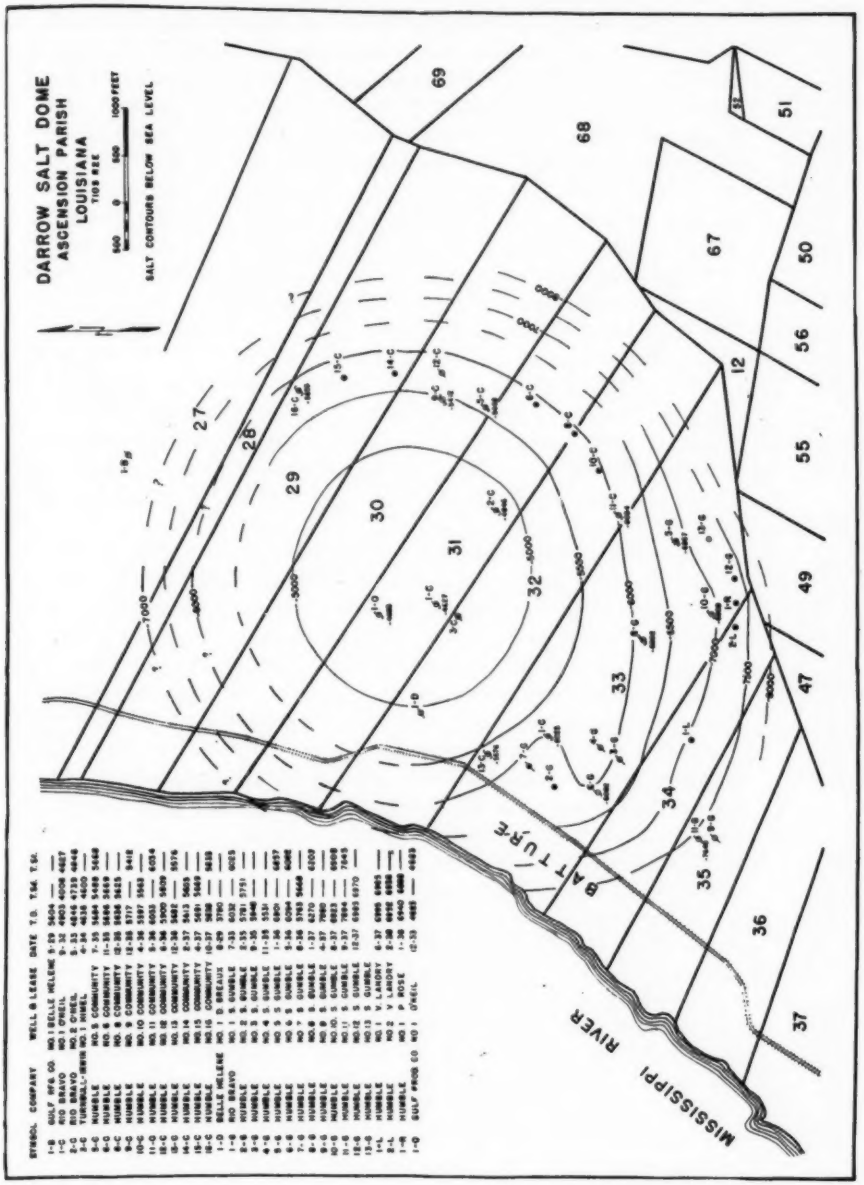

FIG. 2.—Salt map of Darrow dome with data on all wells.

Position and age of producing sands.—A small amount of oil was produced by the discovery well from what are probably Miocene sands lying several hundred feet above the cap rock. The important production on the dome was first obtained from sands approximately 5,700 feet deep on the eastern and southwestern flanks, and more recently from sands on the southeastern flank at a depth of approximately 7,000 feet. The producing sands at both levels are lodged against the salt mass at a relatively high angle so that the oil sands cover a narrow horizontal area, and it is most difficult to locate each well advantageously in the oil section. The sands are relatively thin with shale partings of varying thickness. In general, the deeper sands give promise of better recovery per well than has been obtained from the shallower sands.

The oil sands, although found at different depths, are thought to represent the same stratigraphic horizon in the Lower Miocene strata. Occurring several hundred feet below the *Bigenerina floridana* horizon (Shoal River of Florida), the top of the producing section is closely associated with a thin zone characterized by presence of numerous large *Amphistegina*.

Possibility of deeper horizons.—The possibilities are very good for production from deeper sands than are now producing on the dome. As the base of the Miocene section with its many sands would normally be expected below 10,000 feet in the area, production may reasonably be anticipated from any part of several thousand feet of Miocene below the present producing zones. The Oligocene section also offers some promise as a possible source of oil, though the porosity at Darrow may not be comparable with that in sands of the same age in fields farther updip. The deeper production on the almost vertical face of the salt mass will add little to the actual surface area embraced by operations, as the two producing belts are assumed to have parallel trends on the east side of the dome approximating the positions of the 6,000- and 7,500-foot salt contours.

Paleontologic key beds.—The Miocene penetrated at Darrow has fairly well defined paleontologic horizons, but these are difficult to determine from cuttings and non-recognizable by the driller so that a considerable amount of coring is necessary above the depth at which the oil sands are anticipated. This lack of readily identifiable key beds necessarily adds substantially to the cost of operations, particularly where considerable faulting is involved in the flank sands.

Geologic history.—Because of the lack of anhydrite and gypsum cap rock on the dome, it may be assumed that the dome is geologically somewhat young. This is borne out by the fact that a thick section of

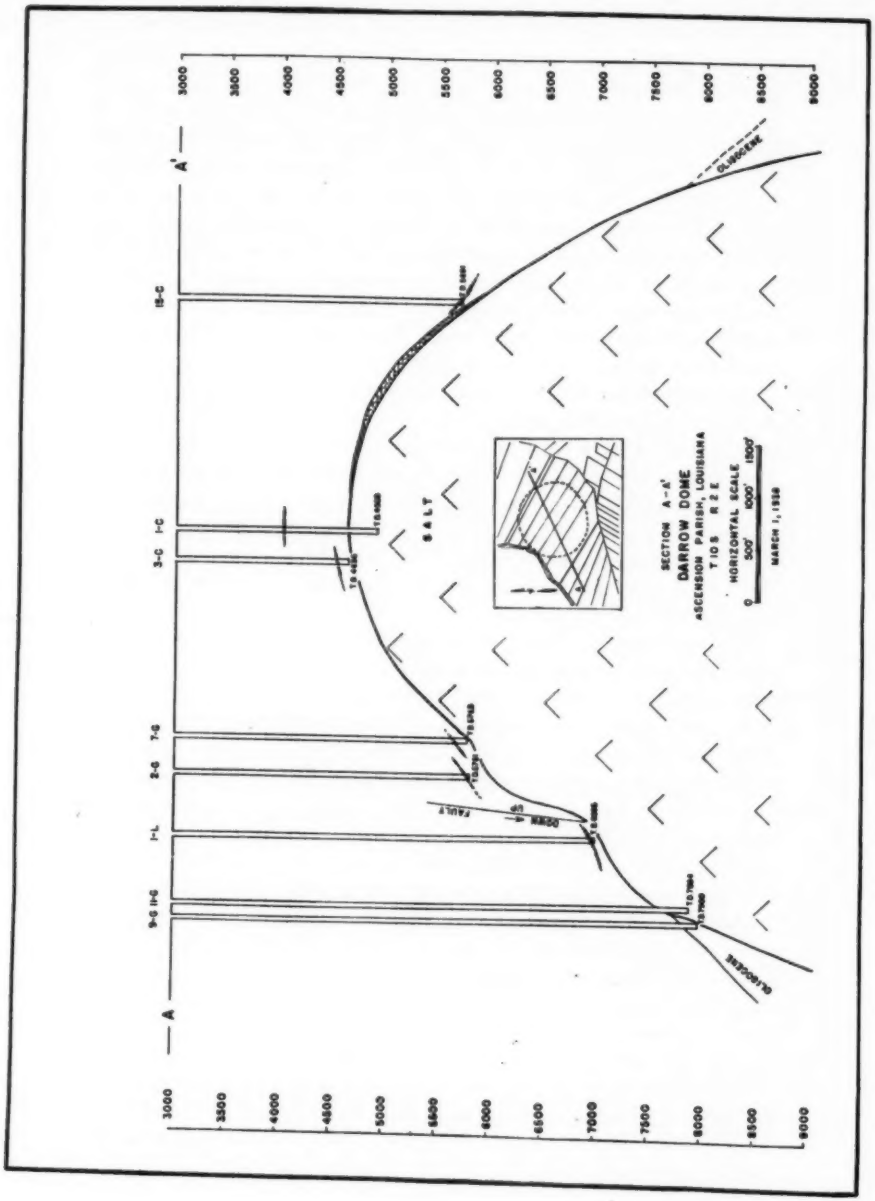

FIG. 3.—Southwest-northeast cross section of Darrow dome.

shales at about 3,100 feet over the dome seems appreciably less disturbed than the lower strata, thus the dome must have penetrated the strata almost to its present position in early Pleistocene time with slight movement since that age. The oil must have accumulated in the present sands during a resting stage in the life of the dome just after the completion of the Shoal River stage. Subsequent disruption of the sands by upward movement segregated the several portions of the sand in their present positions. It is extremely unlikely that the accumulation on the top of the dome could have taken place after the sand had been lifted to its present position, for if the oil were generated in the sand where found, the gathering area would be insufficient. If the oil were not formed in the sand, then it would have been highly improbable that it would have lodged in this particular zone to the neglect of many other porous media present. That some late movement has taken place is apparent from structure on the shallower beds; and that some comparatively recent movement has taken place may be inferred from the fact that the dome has forced the Mississippi River out of its normal course. The dome ascended surfaceward rapidly after penetrating the relatively unconsolidated shales and thick water-bearing sands of the Miocene section, else it would have accumulated a more massive cap rock through the solvent action of these waters.

Origin of dome.—The Gulf Coastal Plain of Texas and Louisiana has undergone considerable flexing, as vertical warping has proceeded there since post-Paleozoic time. This type of movement has resulted in several tension fault systems affecting surface beds from Cretaceous to Pleistocene in age. These are best studied and understood in those areas where the surface beds are most easily mapped. The opinion is ventured here that many of the Louisiana and Texas salt domes have originated from these faults and fault systems, of large or small degree, which sheared the salt strata and disturbed the equilibrium of adjacent areas. The differential pressure created by a few feet of vertical movement along a fault plane, together with ease of penetration afforded by rupture of the strata, seems sufficient to initiate the growth of a salt fold which would subsequently attain cylindrical form with continued upward movement. Although these fault systems are best exposed in Texas, there is good reason to believe that they are present, though not so easily recognizable, across the entire Gulf Coast salt basin. That the domes do not follow regular patterns does not seem a valid argument against this type of origin, for even where mappable on the surface of the older beds, many fault systems present amazing designs.

Amount of uplift.—The amount of uplift in the producing sands appears to vary from a few hundred feet in the deepest flank sands to more than 3,000 feet for the sand on the top of the structure. Fragments of beds older than Miocene have been found here and there pushed upward on the face of the salt, but on the south flank heaving shale, thought to be Oligocene in age, was encountered at 7,980 feet, or several thousand feet above its normal position. It is worthy of note that some of the deeper strata encountered in the Mississippi delta region are reported to contain faunal assemblages more typical of the Mexican strata than that commonly encountered in the strata of the Texas-Louisiana Gulf Coast Plain.

Drilling operations.—To January 1, 1938, thirty wells had been drilled on or in the vicinity of the dome of which ten were commercial wells. Because the sands were difficult to locate, much sidetracking has been done, and the total depth of the original wells does not give any true indication as to the amount of footage actually drilled or the amount of time and money expended in the operation.

All drilling operations in southern Louisiana and, particularly, the delta region of the Mississippi and Atchafalaya rivers are confronted with the problem of successfully penetrating unconsolidated sediments containing a large proportion of massive sand and gravel strata of Pleistocene, Pliocene, and Miocene ages. This situation prevails at Darrow and interesting results were observed, particularly in the case of cement plugs set for sidetracking purposes. It was found that the mud fluid flowed into some of the deeper sands at such a rapid rate that only the core of the cement plugs was enabled to set, and the plugs themselves would be found considerably below the original setting position. As the plugs were in motion during setting time, there was no combination with the walls of the hole, and additional cementing operations were necessary. It seems quite possible that this same type of condition may have affected many operations where casing cement jobs were defective. At Darrow, the percentage of sand section may conservatively be estimated at more than half of the total sediments penetrated.

The depths to the oil sands in the upper flank-producing area vary from 5,488 to 5,751 feet, probably due to faulting. This factor also probably accounts for the fact that the gravity of the oil obtained from the respective wells varies from 33° to 41.8° A.P.I. In the deeper and recently discovered producing level, the top of the sand is found from 6,888 to 6,985 feet and the oil is approximately 39° A.P.I. gravity.

The deepest well drilled on the dome was the Gumbel No. 9 on

the south flank, which was abandoned in heaving shale of Oligocene age at 7,980 feet. This well had a very short section between the Middle Miocene and the Oligocene, hence there is a possibility that the missing section of hundreds of feet may be found lensed out against the dome downdip from this structural position.

OIL PRODUCTION

Because the production is practically confined to the flank belts which are of limited horizontal extent, the actual proved area at the end of 1937 was only about 40 acres. It is thought that the present belts may extend around the dome at approximately the same relative positions with respect to the salt contours but both are probably very narrow.

Cost per barrel of oil produced on the dome has been relatively high because of the hazards of structure involved and compares unfavorably with super-cap production from sands at the same general depth. On December 31, 1937, daily production of 2,074 barrels was being obtained from eight wells, and the dome had produced 1,518,921 barrels of pipe-line oil to the end of the year.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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CRETACEOUS AND EOCENE STRATIGRAPHY OF BARRILLA AND EASTERN DAVIS MOUNTAINS OF TRANS-PECOS TEXAS[1]

C. T. JONES[2]
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ABSTRACT

Cretaceous sedimentary formations and Eocene volcanic rocks crop out in, and adjacent to, the Barrilla and Davis mountains of trans-Pecos Texas. The Lower Cretaceous (Comanche series) is represented by a basal section of Trinity (?) and Fredericksburg age; a medial section consisting of Comanche Peak limestone, the Edwards formation, and the Kiamichi clay all of Fredericksburg age; and an upper portion of Washita age made up of the Georgetown limestone and the overlying Grayson clay and Buda limestone. Only the top member of the Washita group, the Buda limestone, crops out contiguous to the mountain front.

The Upper Cretaceous (Gulf series) is represented by the Eagle Ford, Austin, and Taylor formations. The basal Upper Cretaceous, the Woodbine sand, is absent and Eagle Ford strata are in contact with the underlying Buda.

Of considerable interest is the unconformity between the Cretaceous and Eocene. Before the volcanic rocks encroached, the land surface was very flat and gently inclined as great uniformity characterizes the lava flows. A few lake deposits are associated with the basal igneous section. Each lava flow maintains constant lithologic characteristics and can be recognized from hand specimens with one exception.

These volcanics can be used to good advantage in structure mapping because they reflect the folding affecting underlying sediments and extend over wide areas with relatively uniform change in thickness and interval.

It is evident that the source of these extrusions was at the west and southwest. A constant increase in thickness and quantity of intrusive activity in that direction tends to substantiate this assumption.

INTRODUCTION

The Barrilla and eastern Davis mountains are in parts of Reeves, Jeff Davis, Pecos, and Brewster counties, trans-Pecos Texas, and flank the Toyah structural and topographic basin on the southwest. The Barrilla Mountains are actually a northeastward outlier of the Davis Mountains, one of the prominent ranges of the region, and separated from them by a pronounced syncline through which flow the headwaters of Limpia and Toyah creeks (Fig. 1). Baird Mountain is a topographic crest at the southeastern extension of the Barrilla Mountains.

The eminences of the Barrilla and Davis mountains are a result of both folding and the resistant character of the strata. Elevations of the piedmonts are approximately 3,500 feet; the topographic crest of the Barrillas has an elevation of 5,532 feet; Star Mountain (Fig. 2), on the eastern extremity of the Davis Mountains, reaches 6,350 feet,

[1] Published by permission of the Stanolind Oil and Gas Company, Tulsa, Oklahoma. Manuscript received, August 2, 1938.

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DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

TEXAS
FORT DAVIS SHEET

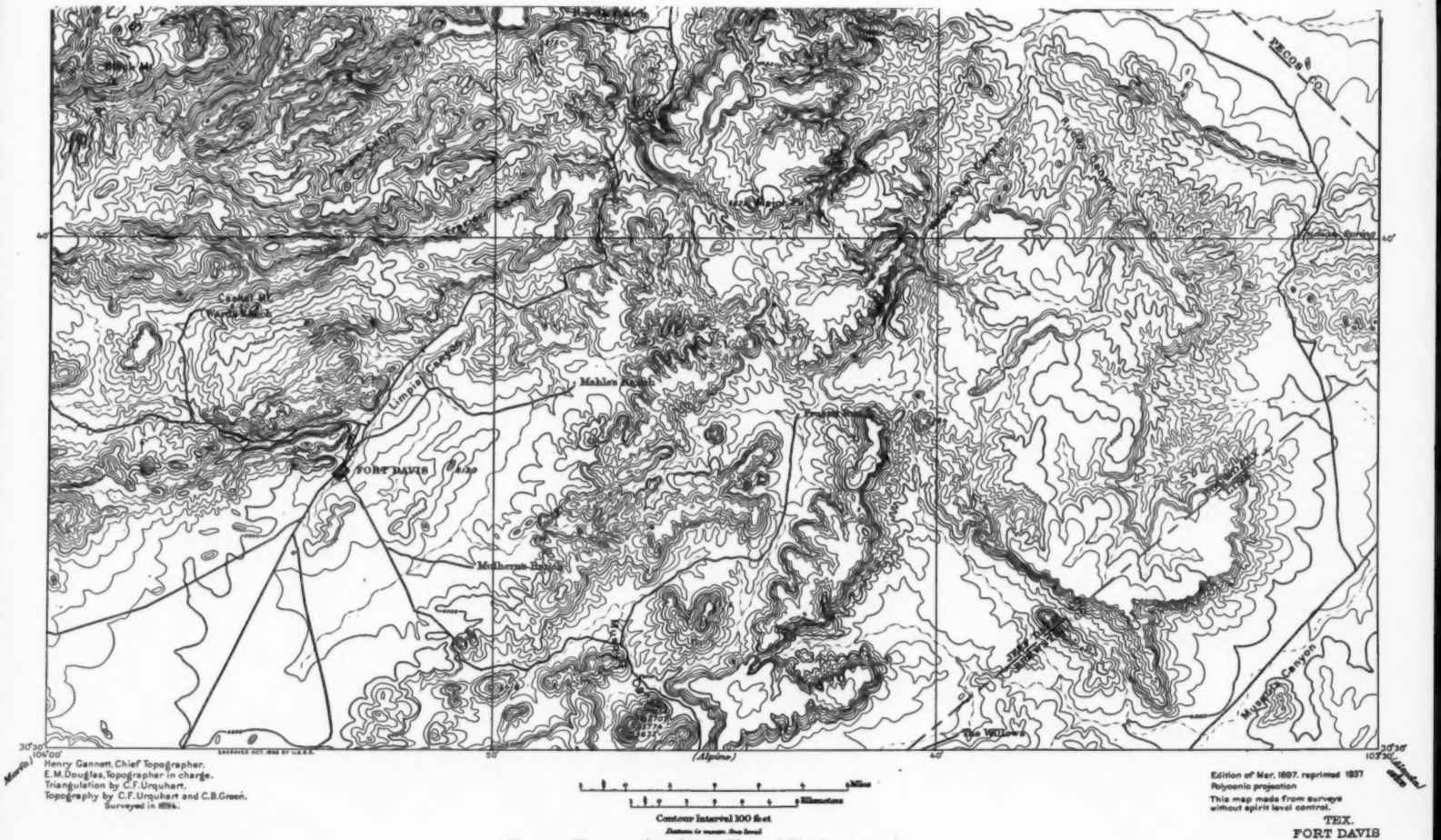

FIG. 1.—Topography of Barrilla and Davis mountains.

and other heights in the Davis Mountains farther west are more than 7,500 feet in elevation. The higher elevations are ordinarily flat mesas of lava; sharp peaks are comparatively rare. Arduous walls and precipitous cliffs do occur along the streams and canyons where perennial water is present with accompanying copious vegetation.

Due to the ruggedness of the terrane, roads are generally confined to the valleys. An all-weather highway connecting Fort Davis and Balmorhea, the two towns in the area, traverses the upper courses of Limpia Creek. Views from this road of the surrounding terrane are spectacular both from a geologic and scenic point of view.

FIG. 2.—View of Star Mountain northwest from Limpia Canyon, showing Taylor sedimentary flats, thick basal rhyolite lava, and overlying succeeding flows.

W. G. Moxey assisted in this work which was accomplished in 1936 for the purpose of determining the structure of the area. It is hoped that this article can be supplemented by a study of the structure. Grateful acknowledgment is expressed to R. I. Dickey who aided in the subsurface determinations of wells drilled in the area.

Because of the great relief and the abrupt changes in gradient, many areas, especially along the lower courses of the streams where they debouch from the mountains into the flats of sedimentary outcrop, are covered with mantles of recent alluvium in the form of fans. These were omitted on the accompanying areal map (Fig. 3) for the sake of clarity, and it should be understood that the map submitted herewith presents a picture of the outcrops with this alluvium, where present, deleted.

LOWER CRETACEOUS STRATIGRAPHY

Although the Buda limestone member of the Washita group is the oldest Cretaceous outcropping immediately adjacent to the mountain

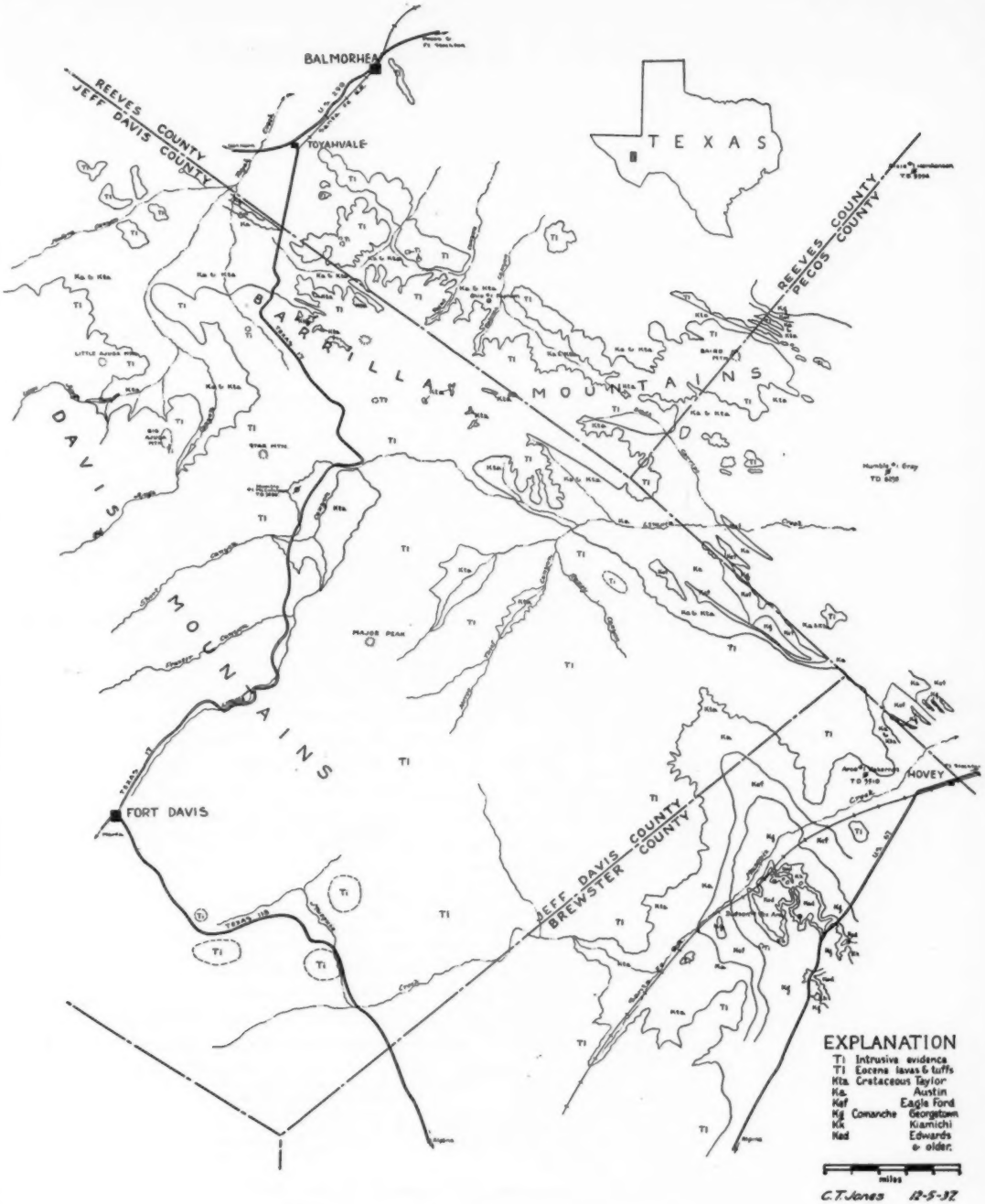

FIG. 3.—Areal geology of Barrilla and Davis mountains.

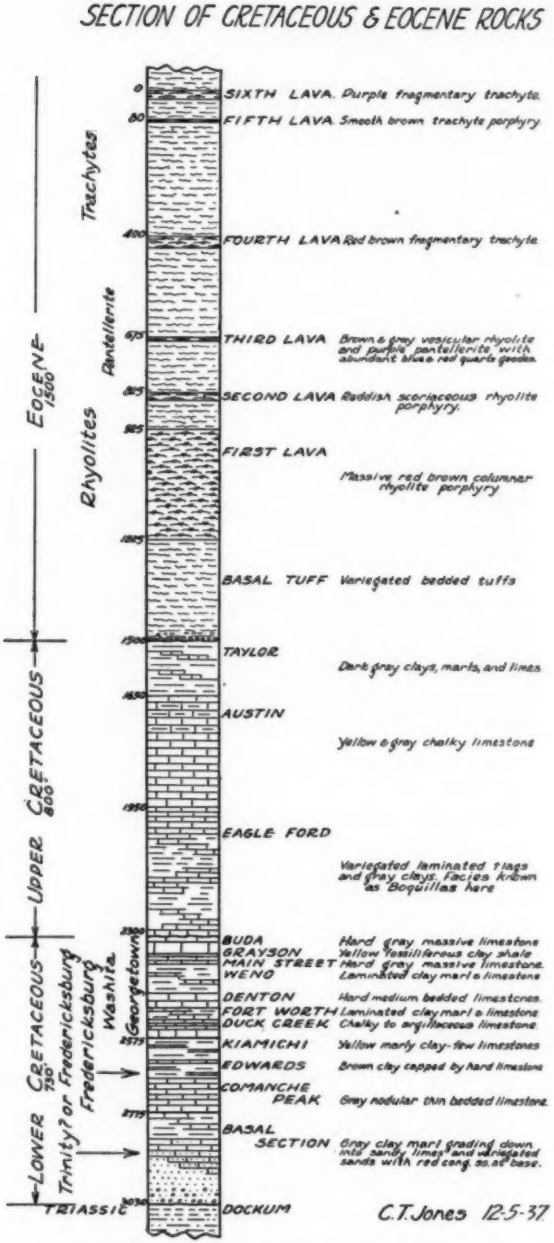
SECTION OF CRETACEOUS & EOCENE ROCKS
EOCENE 1500
Trachytes
Pantellerite
Rhyolites
SIXTH LAVA. Purple fragmentary trachyte.
FIFTH LAVA. Smooth brown trachyte porphyry.
FOURTH LAVA Red brown fragmentary trachyte.
THIRD LAVA Brown & gray vesicular rhyolite and purple pantellerite with abundant blue & red quartz geodes.
SECOND LAVA Reddish scoriaceous rhyolite porphyry.
FIRST LAVA
Massive red brown columnar rhyolite porphyry
BASAL TUFF Variegated bedded tuffs
UPPER CRETACEOUS 600
TAYLOR
Dark gray clays, marls, and limes
AUSTIN
Yellow & gray chalky limestone
EAGLE FORD
Variegated laminated ? lags and gray clays. Facies known as "Boquillas here
LOWER CRETACEOUS 750
Georgetown
Fredericksburg
Washita.
Trinity? or Fredericksburg
BUDA Hard gray massive limestone
GRAYSON Yellow fossiliferous clay shale
MAIN STREET Hard gray massive limestone.
WENO Laminated clay marl & limestone
DENTON Hard medium bedded limestones.
FORT WORTH Laminated clay marl & limestone.
DUCK CREEK Chalky to argillaceous limestone.
KIAMICHI Yellow marly clay- few limestones
EDWARDS Brown clay capped by hard limestone
COMANCHE PEAK Gray nodular thin bedded limestone.
BASAL SECTION Gray clay marl grading down into sandy limes and variegated sands with red cong. at base.
TRIASSIC
DOCKUM
C.T. Jones 12-5-37

FIG. 4.—Columnar section of Cretaceous and Eocene strata.

front, other Lower Cretaceous formations are exposed a few miles southeast in the vicinity of Hovey. These beds were encountered in the Humble Oil and Refining Company's McCutcheon No. 1 well drilled in Limpia Canyon, just south of Star Mountain, and in the Dixie Oil Company's Herschenson No. 1 well drilled a few miles northeast of Baird Mountain. A stratigraphic description of these rocks is, therefore, included herewith.

BASAL SECTION

Overlying a section composed of considerable red sand and some red limestone, which is not entirely typical Dockum (Triassic) in character and is classed by some as Bissett (Lower Cretaceous), are approximately 250 feet of strata which are either late Trinity or early Fredericksburg in age. In the Humble well in Limpia Canyon this section is approximately divisible into two parts; the basal half consists of light gray limestones, dark gray shales, variegated sandy limestones, and medium-grained soft ferruginous angular sands with a distinct conglomeratic zone at the base; the upper half is made up of interbedded gray limestone and dark gray shale.

In the Dixie well the basal Cretaceous section is similar except that the lower half is more arenaceous, the sands being more variegated in color and greater in quantity with the basal section much coarser and conglomeratic.

The outcrops of this basal section in closest proximity to the mountains are in west-central Pecos County where they consist of reddish and brown ferruginous laminated sandstones.[3] A great variation in thickness and character of these strata is evident and is the result of the undulating pre-Comanche land surface which the early Cretaceous sea invaded. Whether the basal strata in the Barrilla area are Trinity or Fredericksburg or both is not definitely shown, but in a well drilled a few miles west of Hovey evidence has been presented that the basal Cretaceous beds encountered were probably Trinity in age.[4]

As the invasion of the sea was from the south and the evidence cited in the foregoing paragraph is considered extraordinary in that it is some distance north of exposures of unquestioned Trinity age, it is extremely doubtful if the basal Cretaceous section underlying the Barrilla area is older than very late Trinity. Furthermore, evidence indicating Fredericksburg age has been found from the upper beds of

[3] W. S. Adkins, "The Geology and Mineral Resources of the Fort Stockton Quadrangle," *Univ. of Texas Bull. 2738* (October 8, 1927), p. 32.

[4] *Ibid.*, p. 34.

this basal section at the outcrop in the vicinity of Fort Stockton.[5]

It is worthy of note that most well sections of this basal sand are thicker than most measured outcrop sections and, furthermore, apparently contain a greater amount of calcareous material. This may be because most surface exposures are believed adjacent to pre-Comanche topographic "highs" and, therefore, did not receive a maximum of basal Cretaceous deposition.[6]

FREDERICKSBURG GROUP

Conformably overlying the basal section is the Fredericksburg group, 200 feet of fossiliferous limestones, marls, and clays. This series consists of the Comanche Peak limestone at the base, the medial Edwards formation, and the upper Kiamichi clay. It is present in all wells drilled in, and adjacent to, the Barrilla area and crops out on the Hovey dome southwest of Hovey.

The Comanche Peak limestone is about 90 feet thick and consists of soft nodular, thin-bedded, argillaceous, grayish buff limestone at the base grading upward into a more indurated similar section. It crops out in a series of benches due to the presence of laminae of different thickness and hardness, the indurated rudistid-bearing strata forming cap rocks. It is believed that this limestone contains the equivalent of the Walnut clay.[7]

Conformably overlying the Comanche Peak is the Edwards equivalent consisting of slightly more than 50 feet of soft calcareous shale and marl capped by a hard 4-foot bed of buff limestone. This section has been referred to as the University Mesa marl.[8] The top indurated bed forms very prominent benches and supports many ocotillo thickets. The underlying fossiliferous clay and marl, being much softer although containing some limestone laminae which are well exposed on the Hovey dome, is in may places concealed by talus. On the outcrop it displays a brown ferruginous color in contrast to the Comanche Peak limestone beneath.

Conformably the Kiamichi clay overlies the Edwards, is a little more than 60 feet thick, and consists of fossiliferous ferruginous-stained yellow marly clay containing a few soft lighter beds of limestone. It ordinarily crops out on the steep talus slopes of hills capped by the basal Georgetown or Duck Creek limestone and appears as a barren light brown or yellow band across the landscape.

[5] W. S. Adkins, *op. cit.*, p. 33.

[6] *Ibid.*, pp. 36–37.

[7] W. S. Adkins, *op. cit.*, p. 37.

[8] "The Geology of Texas, Vol. 1, Stratigraphy," *Univ. Texas Bull. 3232* (August 22, 1932), p. 339.

WASHITA GROUP

The Washita group, as determined from its outcrop west of Hovey and from well sections in, and adjacent to, the Barrilla area, has a thickness of approximately 275 feet. Because, in the wells, the section appears to be predominantly limestone and the individual members of the group are indeterminable, it has been referred to as the Georgetown limestone and is thus shown in Figure 3.

However, in the vicinity of Hovey the individual members are distinguishable and compare favorably with other outcrops on the east toward Fort Stockton.[9] A soft white nodular fossiliferous limestone, the Duck Creek, overlies the upper Fredericksburg or Kiamichi clay with apparent conformity. This lower cap rock is succeeded in ascending order by the following members: the Fort Worth limestone, the Denton limestone, the Weno formation, and the Main Street limestone. North of Hovey the Main Street or upper Georgetown is succeeded by a conformable, thin fossiliferous yellow clay, the Grayson, containing an abundance of *Exogyra arietina*.[10] At the top of the Washita group and conformably overlying the Grayson is the prominent Buda limestone, white to gray, hard, fine-grained evenly bedded limestone containing many ferruginous and coralliferous laminae, especially near the top. It weathers into hard white blocks which, due to their very resistant character, may easily be recognized. This member of the Washita group crops out adjacent to the mountain front and perhaps is exposed a maximum of 40 feet in thickness.

The Dixie Oil Company's Hershenson No. 1 commenced a few feet above the Georgetown-Kiamichi contact, topping the Kiamichi close to 25 feet. There was, therefore, approximately 475 feet of Cretaceous sedimentary rocks encountered in this well.

UPPER CRETACEOUS STRATIGRAPHY

As the Woodbine sand is missing in this area, the eroded surfaces of the Buda limestone are overlain by Eagle Ford strata with an undulating contact. The Eagle Ford, or Boquillas flags, as the facies has been termed in this area,[11] consists of salmon- to lavender-colored, even-bedded and laminated hard dense flags and bluish gray calcareous shale. Gypsiferous material is locally present. Most of the

[9] W. S. Adkins, *op. cit.*, pp. 42–48.

[10] "The Geology of Texas, Vol. 1, Stratigraphy," *Univ Texas Bull. 3232* (August 22, 1932), p. 394.

[11] *Ibid.*, p. 423.

strata are dark gray at the fresh outcrop but rapidly oxidize into the lighter colors. A thickness of 350 feet was measured in the area.

With a somewhat gradational contact the Austin next occurs. It is possible, however, to distinguish the same contacting strata at different exposures because, stratigraphically upward, the flagstones abruptly disappear even though a gradational increase in chalk occurs. This transition is accomplished within 20 feet of section and the contact used in the mapping was the top of the flagstones which, being generally a little harder than the overlying chalky stratum, forms a low bench, but above, by approximately 20 feet, the first typical chalky Austin limestone appears. In the Barrilla area, in contrast to other localities, the Austin is a little more resistant to erosion than the Eagle Ford; therefore, Austin outcrops are more common than Eagle Ford.

The Austin consists of white, chalky limestones at the base, grading upward into gray marly limestone which weathers into white and yellow chalk and yellow clay. *Inoceramus subquadratus* casts are plentiful and the upper half of the formation consists of much more clay and shale than the lower half.

The Taylor and Austin are conformable. In fact, upper Austin and lower Taylor can not be differentiated lithologically. *Exogyra ponderosa*, diagnostic of this section, was observed at many exposures; some of these forms reached the remarkable size of more than 3 inches in diameter. *Gryphea newberryi* was recognized from the Taylor marls and clays. A thickness of 450 feet was measured for Austin and Taylor beds; of this, approximately 300 feet is assigned to the Austin.

Since an hiatus occurred, at least after basal Taylor deposition and previous to the encroachment of the first Eocene volcanic rocks, a prominent zone of lixiviated material is locally present at the top of the Taylor marls. This zone commonly appears in banks of yellow clay abundant with pelecypods and forms a prominent band of color and vegetation along the foot of the basal lava escarpment.

The Humble Oil and Refining Company's McCutcheon No. 1 commenced a few feet below the base of the Eocene volcanic rocks in the top of the Taylor and found the base of the Upper Cretaceous at about 1,130 feet. Included in this 1,130 feet, however, was an igneous sill, 390 feet in thickness, entirely confined to Eagle Ford strata. As the base of the Lower Cretaceous was found at approximately 1,860 feet, about 1,470 feet of Cretaceous material was present in this well.

TAYLOR-EOCENE UNCONFORMITY ZONE

A major unconformity exists in the area between the basal Taylor and the first volcanic rocks (Fig. 5) which have been assigned an

Eocene age due to the occurrence of limited fauna and flora. The upper part of the Taylor, and the normally overlying Navarro, are missing and it is not determinable whether their deposition ever occurred in the area.

A period of deformation, known as the Laramide and of great prominence and duration in the Rocky Mountain region, occurred during this hiatus, and throughout trans-Pecos Texas the sedimentary-igneous contact varies in the age of the contacting strata. However, throughout the area under discussion, the basal volcanic rocks are at all exposures in contact with the Taylor marls and clays, and in

FIG. 5.—Pebbles in tuffaceous sand matrix. Taylor-Eocene unconformity zone.

most places *Exogyra ponderosa* is identified from strata immediately subjacent to the basal volcanic stratum. Therefore, little flexing, if any, resulted from this period of deformation in the Barrilla area.

The unconformity zone varies in thickness from a clean-cut contact of lava and sediments, with an expected marmarized zone, to 60 feet. Many facies of this zone occur, some of which are herewith tabulated: (1) gray clay underlying white tuff; (2) gray clay containing pebbles and cobbles underlying white tuff; (3) white to gray fine cross-bedded tuffaceous sand containing pebbles underlying white tuff; (4) typical weathered yellow Taylor clay under white tuff; (5) indurated yellow and brown quartzitic sand with pebbles under tuff; (6) pebbles of Taylor or Austin limestone or marl under tuff; (7) white and buff tuff cross-bedded with pebbles; and (8) lava flows in direct contact with marls with no zone of weathering but with evidence of metamorphism of subjacent strata.

The pebbles and boulders of this zone are of especial interest. Their source is undoubtedly the Glass Mountain and Marathon areas on the

southeast because, as this zone is traced in the field in that direction, the black chert content, recognized as Maravillas, obviously increases. The pebbles also include material from Comanche limestones and Permian limestones and quartzites. All pebbles are well rounded but flat, ordinarily with three unequal axes—one comparatively long and one comparatively short—and vary from $\frac{1}{4}$ inch in diameter to cobbles as large as 2 feet in diameter. The gravels commonly occur in "banks," not necessarily being continuous between outcrops, although some are disseminated throughout the unconformity zone at some exposures.

FIG. 6.—View west of Big Ajuga Canyon from northwest flank of Star Mountain.

This unconformity is a prominent water-seepage plane and vegetation is generally more prolific at this zone. Throughout all the area investigated, few seeps or springs were found which did not emanate from this zone.

EOCENE VOLCANIC ROCKS

Although extrusions in the form of lavas and tuffs constitute the greater amount by far of Eocene volcanic rocks, locally there are associated with these beds some sedimentary rocks but their occurrence is extremely rare.

These lenticular, fine-grained, tuffaceous beds are thought to be lake deposits and are found only in the basal igneous section, in the main composed of tuffs. In one locality along both sides of Limpia Creek near the Jeff Ranch, such a deposit crops out a short distance stratigraphically over the unconformity zone. It consists of very fine-grained, calcareous, hard tuff containing casts of a mollusk, probably *Helix*.

Although the evidence pointing to an early Tertiary age of these lava flows and tuffs is entirely conclusive, sufficient evidence has not yet been presented positively to place their age within a definite part of Eocene time.[12] It is regretted that no definite evidence was discovered during the course of the work which would add to that found in the current literature.

In the Barrilla area an igneous section of 1,500 feet in thickness was measured. Westward, in the eastern Davis Mountain area, in the vicinity of Star Mountain, this section had increased to about 1,800 feet due primarily to a thickening of the basal flow. Farther west in

FIG. 7.—Short Canyon showing thick basal flow.

the Davis Mountains (Fig. 6) the section is believed to have thickened tremendously but no detailed work was carried back that far because less uniformity appeared in the later basaltic flows, due to an increased amount of intrusive activity.

A definite sequence in the stratigraphy of the igneous section exists in the trans-Pecos:[13] (1) basalts (Pliocene) at top, (2) andesites, (3) trachytes, (4) pantellerite-paisanite, and (5) rhyolites at base.

The igneous rocks of the Barrilla and Davis area tend to conform with the basal part of this sequence and farther west from the area under discussion, where younger volcanics come in over the Barrilla section, basalts crop out.

The common section in the area, ascending from the unconformity, consists of a lower tuff section of hard and soft, coarse- and fine-

[12] "The Geology of Texas, Vol. 1, Stratigraphy," *Univ. Texas Bull. 3232* (August 22, 1932), p. 804.

[13] *Ibid.*, p. 805.

grained, white to buff tuffs which, near the base, contain large quantities of fossil wood and stumps as thick as 3 feet in diameter. Over this are other tuff and ash beds, in places concealed by talus from the thick overlying basal lava flow, which are softer and darker in color. At many exposures of this upper section, thick banks of dark gray and black ash with bombs, much calcite, and green secondary copper veining, are found.

Next, a 300-foot flow of massive red and brown rhyolite porphyry occurs. This lava is the main cliff-former of the region and in many places crops out in two benches, each exhibiting columnar jointing to some extent. It thickens to 615 feet in the Star Mountain area (Fig. 7), and farther west, on the flanks of Timber Mountain, appears to have increased to nearly 1,000 feet in thickness.

Immediately overlying are more white to buff bedded tuffs followed by the second lava flow, a rough-surfaced, red to orange scoriaceous rhyolite porphyry. This stratum, although only 20 feet thick, is widespread and maintains a somewhat constant stratigraphic interval of 100 feet over the thick basal lava flow.

The third lava flow is both underlain and overlain by the most prominent tuff section in the area. These well indurated tuffs are white to buff in color, harder than common, and weather into all sizes of granular blocks. The third lava consists of brown but predominantly blue and gray vesicular rhyolite. It has the physical appearance of basalt when examined megascopically but the color is misleading as it contains an abundance of quartz. At some exposures of this bed, a very extraordinary rock was found. It closely resembles, and may be defined by, the type pantellerite, being intermediate between rhyolite and trachyte in one classification, and between pantellerite and dacite in another. This rock is dark purplish and has a plagioclase felsitic groundmass with large phenocrysts of blue and pink quartz in the form of geodes and druses. This stratum evidently is correlative with No. 4 of the aforementioned sequence; the lower two flows, of course, being the complements of No. 5, and the next succeeding flows above, being trachytes, are the correlatives of the No. 3 group. This third lava is only a minor flow, being just 8 feet in thickness, and is not as widespread as the rest of the extrusions. It is 150 feet stratigraphically above the second flow and 675 feet below the top of the igneous section exposed in the area.

The fourth lava consists of some red but predominantly brown fragmentary crystalline trachyte. In the Barrilla area, it has a thickness of 25–50 feet but toward the southwest it thickens to more than 100 feet. It is a very prominent scarp-forming bed (Fig. 8) and

has a rather uniform and even top and base. It is 400 feet below the top of the section and 275 feet above the third lava flow.

Overlying are more white to buff tuffs which in turn are succeeded by smooth brown trachyte porphyry with a very fine-grained groundmass; this fifth lava flow is only 5 feet thick. It is 80 feet below the top of the section and 320 feet above the fourth flow. In many places it is concealed by talus from the overlying bench-forming lava.

At the top of the igneous section is brown-surfaced, purple and blue fragmentary crystalline trachyte lava, the sixth flow. It forms a prominent scarp and averages approximately 25 feet in thickness; the

FIG. 8.—Dip slope of fourth laval flow on northeast flank of Star Mountain. Strike N. 60° W., dip 14° NE.

top and base are rather even and uniform. Farther west and southwest, it is succeeded by younger extrusions but these were not investigated during the course of the work because of their apparent variation.

The lava flows of the Barrilla and eastern Davis mountains are very remarkable because of several facts. First, although a lithologic change is accomplished from rhyolites below to trachytes above, each flow maintains its own common characteristics over the whole area. Thus, in areas of much faulting and deformation, of which there are many, each flow can be determined, megascopically, from a hand specimen, with the possible exception of the thick basal flow and the thinner second flow which can be confused unless observed at the actual outcrop. For these the thickness of the outcrop is the governing criterion.

Second, these lava flows are extensive over large areas. They may

be traced farther north and south, or along the strike of the igneous front, than east and west. It is evident, therefore, that these flows encroached over a very flat and gently inclined surface, the pre-Eocene terrane being well base-levelled.

Third, it has been shown that these lava flows thicken toward the west and southwest but this thickening is very uniform and gradual. Perhaps the greatest amount of thickening, both in relation to the total thickness of the igneous section and to one single flow, is in the basal flow. It is apparent then that the source of this lava must have been in that direction. It is west and southwest, in the vicinity of

FIG. 9.—Domal igneous uplift southeast of Fort Davis along Alpine road.

Fort Davis, where major intrusions and igneous uplifts make their appearance. It is considered, therefore, that the source of these volcanic rocks was in the Davis Mountain area west of the town of Fort Davis.

INTRUSIVES

Although considerable areas of the Davis Mountains have been severely intruded, only a few evidences of intrusives exist in the Barrilla Mountain area where several small intrusive plugs were found. The material in these plugs consists of two facies: (1) an agglomerate of red to brown rhyolite with imbedded fragments of other volcanic and sedimentary rocks; and (2) purple and brown crystalline trachyte, similar to the fourth and sixth lava extrusions. These plugs were surrounded by a metamorphosed rim which weathered into the form of a circular depression around the periphery of the plug.

Prominent intrusions are present in the south part of the Fort Davis topographic sheet in the Davis Mountains (Fig. 9). These have

formed domes of circular shape and somewhat pronounced uplift. The lava beds occupying the depressions between these domes are either flat or very greatly inclined. Not all the areas shown in Figure 3 consist of actual igneous intrusions but a prominent circular doming of older extrusions was considered positive evidence of subterranean intrusive action and uplift.

In the Humble well, drilled in Limpia Canyon, 390 feet of intrusive material was encountered in Eagle Ford strata between the depths of 480 and 870 feet. As no evidence of intrusions was found in outcrops of sedimentary rocks in the area, this sill is evidently local. That a distinct doming of the strata occurs in this immediate area is considered the resultant of this and possibly other intrusive sills. It is suggested that the quaquaversal structure known as the Hovey dome, southwest of Hovey, currently being tested by Dodson *et al.*, Texas American Syndicate No. 1, may also be the resultant of subterranean igneous activity.

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THE GEOLOGIST AND THE WELL-SPACING PROBLEM[1]

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ABSTRACT

Following a summary of recent and widely accepted engineering thought on well spacing, geologic phases of the problem are outlined and discussed. Need of a revised viewpoint on the part of the geologist toward wider well spacing in view of new producing conditions is emphasized.

INTRODUCTION

The geologist, of the technical men in the oil industry qualified to have an opinion, appears to be the most skeptical concerning adequate recoveries under wider well-spacing patterns than were formerly used or are now in use in many areas. In attempting to convince geologists that under modern producing conditions recoveries equal to, or greater than, those formerly obtained are possible with wider well spacing, it has become evident that many of them although realizing the economic necessity of such wider spacing do not fully recognize the engineering and geologic factors involved.

One important reason for this doubting attitude may be that geologists as a whole have lost intimate contact with producing fields. In the past, when the old methods of open-flow, untubed, unrestricted production were practiced, geologists were in close touch with drilling and producing operations and formed definite opinions concerning drainage areas, interference patterns, and recoveries. At present the production engineer has, in large measure, replaced the geologist as the technical representative confronted with development and production problems of new fields where modern methods of production, including restricted flow forced on the industry by proration, are practiced. Most geologists, therefore, formulated opinions based on old field experience and they have not had the opportunity to revise those concepts after close observation and intimate field contact with the newer prorated and restricted production methods.

It is the purpose of the writer briefly to outline the most recent and widely accepted engineering thought on the subject of well spacing and to point out some of the salient corresponding geologic interpretations.

Committees of engineers, lawyers, and operators of the American Petroleum Institute and Independent Petroleum Association of

[1] Manuscript received, August 1, 1938.

[2] The Atlantic Refining Company.

America[3] as well as many individuals[4] have given thought and study to legal,[5] economic, and engineering aspects of the well-spacing problem. The legal and economic viewpoints, though important, are not stressed here, but it would be well to refer to W. E. Hubbard's paper, "Economics and Well Spacing in Texas,"[6] and Joseph E. Pogue's "Economic Aspects of Drilling."[7]

These papers in the words of Pogue bring "to a focus the economic advantage of wider well-spacing patterns."

ENGINEERING VIEWPOINT

Mathematical analysis has demonstrated the small influence that gas-well density bears on ultimate recovery from gas fields. MacRoberts[8] in his very fine paper concludes that "Intensive drilling in gas reservoirs will increase the ultimate recovery but slightly."

Stephenson[9] in an even more recent publication points out that high-pressure fields with high gas-"oil" or gas-condensate ratios should be operated as gas fields, which in light of MacRoberts' work indicates that well spacing in that case becomes a matter of convenience and economics and has little relation to drainage.

Although mathematical analysis for fields predominantly oil-producing is not yet possible, experimental work and study by various agencies are going forward and more work is planned which, it is hoped, will lead to analysis similar to that accomplished for gas fields and may even make possible formulation of a correct well spacing for different operating conditions when certain fundamental engineering data are known concerning the reservoir.[10] Though that mathematically accurate formula is not available yet and may never be as

[3] "Report of the Sub-Committee of Nine on Evils Attending Unnecessary Drilling in Proven Fields, and the Remedy" (Independ. Petrol. Assoc. America, 1936 and 1937), *Independent Monthly* (January, September, and December, 1937).

[4] E. A. Stephenson, "Some Consequences of Close Spacing in Kansas" (presented before Amer. Petrol. Inst. Prod. Div., 1938), *Oil Weekly*, Vol. 90, No. 3 (June 27, 1938).
M. G. Cheney, "Economic Spacing of Oil Wells," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 6 (June, 1935), pp. 876–99.

[5] *Legal Phases of Well Spacing*, by the Legal Sub-Committee on Well Spacing of the Committee of the Board of Directors of the American Petroleum Institute on Well Spacing (May, 1938).

[6] *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 123 (Petrol. Div., 1937), p. 163.

[7] *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 22, No. 6 (June, 1938), p. 633.

[8] D. T. MacRoberts, "Relation of Gas-Well Spacing to Ultimate Recovery," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 127, Petrol. Div. (1938), pp. 146–58.

[9] E. A. Stephenson, "Behavior of Contents of High-Pressure Reservoirs," *ibid.*, pp. 189–98.

[10] M. Muskat, R. D. Wyckoff, H. G. Botset, and M. W. Meres, "Flow of Gas-Liquid Mixtures through Sands," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 123, Pet. Div. (1937), pp. 69–96.

exact as desired, still study and experiment have gone forward far enough to make the summation of engineering principles quoted in the following paragraph a generally accepted basis upon which the geologist can begin building a new viewpoint.

The most enlightened engineering viewpoint can best be given by quoting parts of a summary report by the Special Study Committee on Well Spacing presented to the Committee of the Board of Directors of the American Petroleum Institute on Well Spacing in May, 1938, and printed in several trade journals.

ENGINEERING PRINCIPLES IN PRODUCTION OF RESERVOIR

1. It is generally agreed that the maximum rate at which a pool can be produced efficiently and economically can be determined.
2. To gain the greatest ultimate recovery ratable withdrawals from the reservoir must be maintained.
3. The rate of withdrawal materially affects the drainage area of a well. Given the former, engineers may, with reasonable limits, determine the latter. Under restricted withdrawal, regional reservoir drainage results and the drainage area of a well becomes indeterminate, reaching in some cases to remote points in the reservoir. Under such conditions, the efficient drainage area of a well becomes that size of uniform geometrical pattern which will insure adequate wells for reservoir drainage and ratable withdrawal.
4. The same or greater efficiency of recovery can be obtained by wider spacing at lower rates of flow per acre than by close spacing at excessive rates of flow per acre.
5. Well density, within reasonable limits, is not a factor affecting ultimate recovery when ratable withdrawals by the owners of the oil in place is observed in a pool. . . .
6. The maximum ultimate recovery by eliminating underground waste and preventing premature or improper encroachment of water is obtained by the efficient use of reservoir energy, either natural or artificially introduced, limited only by economic considerations.

It should be emphasized that "Engineering Principles" as quoted here are a result of observation and study of pools and reservoirs under proration where production has been through restricted rates of flow. The whole pool, it will also be noted, is considered rather than a well or lease in that pool. Many of the conceptions still held by geologists are based on old "open flow" conditions and involve the single lease or well rather than the pool or reservoir as a whole.

GEOLOGICAL VIEWPOINT

In considering reservoir conditions as related to well spacing the geologist is prone to overemphasize irregularities in the producing horizon. Irregularities in porosity and permeability, unconformities, sand lensing, shale partings, cavities in limestone reservoirs, and

similar phenomena are frequently cited as conditions which make close spacing necessary. The reasoning behind these assertions is not clear. If first we assume that in dealing with this problem only commercial or near-commercial accumulations of oil are involved, then it can confidently be stated that most reservoirs are continuous and have extensive areas of connected porosity or permeability. The very processes of deposition of the sediments forming the reservoir and the processes which induced the porosity entail in most instances a continuity within the reservoir which is sufficient to insure drainage under properly controlled physical conditions.

There is no intention here of minimizing the effect of unconformities, faults, changes of porosity, sand lenses, shale partings, *et cetera*, in limiting the *extent* of a reservoir, but once the geologist has satisfied himself concerning the limits of any one reservoir then the variations mentioned can not materially affect the spacing problem or the degree of effectiveness of drainage.

Much confusion seems to exist in this regard. Knowledge of exact reservoir conditions throughout the field and various parts of it is most important in determining reservoir contents and probable lease or well recoveries (oil in place) or in designing the ideal proration formula for a field to insure ratable withdrawals or in determining proper rates of flow for the field as a whole and for various parts of it. Such knowledge is of only very minor use in the consideration of well spacing.

That this is true and accepted by many geologists is borne out by the statement so often made that "if properly located I can drain a structure (or a pool) with one well (a ring of wells, a line of wells, *et cetera*)." Yet frequently these same geologists will insist that x plus y number of wells are required to drain the lease in which they interested in contrast to x wells on the offset lease, because of differences in porosity, *et cetera*, *et cetera*.

If fields and wells are so produced as to approach the engineering ideal of pressure maintenance and flow of oil to the well bore in the liquid phase, then variation in porosity of even large amount (provided there still remains a reasonable minimum permeability) will not affect drainage. Pressure should be maintained either artificially or by restricting withdrawal from the reservoir to such a rate as to permit edge and bottom water to fill the voided space. If the field is to be produced as an oil field, then gas produced with the oil should be limited to that normally dissolved in the oil in the reservoir and no free gas produced. Withdrawals must be distributed so that no coning of water or depression of the gas-oil contact occurs locally and so that

no large pressure anomalies occur. In reaching such ideal or nearly ideal conditions which make wide well spacing possible, reservoir variations must be fully considered though they have little effect on well spacing itself.

Under such ideal conditions a cavern in a limestone reservoir will be drained as effectively if the well bore penetrates a joint, crevice, or streak of porosity which is connected to the cave as if it taps the cavern itself. Under such conditions, too, a well drilled into a 3-foot sand will drain a near-by and connected lentil 30 feet thick as effectively as a well drilled through the lens itself.

Again this statement is not to be interpreted as meaning that determinations of "oil in place" or proper rates of flow for the wells and field must not take such variations into consideration.

If a limestone contains caverns without connecting joints, crevices, or porous zones, then to drain the cavern only a well which actually penetrates it will serve. A commercial accumulation of oil contained in only one cavern would postulate a large cave, and in that event well spacing within the limits of the reservoir would not be a problem. If there are many small, isolated, unconnected caverns, a spacing that insures at least one well to each cavern would be required and that condition might be used to illustrate one of the few instances justifying close well spacing. However, such a reservoir is difficult to imagine, since it would force the geologist to some bizarre theorization to account for the caverns themselves or the accumulation of oil in them. Either dolomitization or "acid-water" theories explaining formation of porosity or caverns in limestone require percolating or circulating waters or extensive exposure of considerable areal extent to ground water or sub-aerial erosion all of which result in openings or reservoirs having continuity.

Similar reasoning will be found to hold true for sand lenses and in fact for most irregularities within the reservoir. Shale in sand, anhydrite, or secondary deposition in pores of limestone may be present locally and in one plane of deposition, but only exceptionally to such an extent and with such distribution as actually to completely isolate parts of the reservoir. If widespread and important, then such conditions result in a non-commercial accumulation with which we are not concerned in this analysis.

Well spacing from a geological viewpoint then becomes a matter of determining the limits of the reservoir and of determining whether structural conditions are such as will make possible production under conditions previously outlined as approaching the ideal, or, if the desired producing conditions can not be entirely attained, to what extent they might be approached.

Determinaton of the limits of a reservoir entails the principal problem and in most instances is amenable to geologic analysis after a small amount of development. In referring to "limits of reservoir" here it is not meant to imply that the limits of the pool as outlined by dry holes must be known before decisions concerning well spacing can be reached. But it is important to learn whether the reservoir is essentially continuous (irrespective of variations) over the entire structure or whether sand lensing, for example, will be found common. If the latter is true, efforts should be made to drill wells early in such configuration as to assist in determining the limits of the lenses and whether their size is sufficient to insure commercial production. If the lensing is common and because of exceptional conditions of depth or thickness commercial production is possible, then well spacing must be designed to take care of the condition.

"Shoe-string sands," stratigraphic traps, and in fact all forms of commercial accumulation may have specialized problems which confront the geologist in determining "limits of the reservoir"; but once determined by analysis or drilling, the well-spacing decision can be made without further exact knowledge of reservoir irregularity.

The more nearly the ideal producing conditions can be attained the wider the well spacing may be to accomplish the degree of commercially practiced drainage desired. The geologist is especially fitted to determine in the early life of a field whether reservoir conditions are such that casing, perforating, or packer programs designed to eliminate "free" gas will be effective and through what part of the life of the field. He can also help in foretelling whether rates of flow will be possible in widely spaced wells which would insure the ideal engineering conditions or whether such rates would be too low to be economically feasible, making it necessary to sacrifice most efficient production and at the same time drill more closely.

A recent analysis by Porter[11] of the geologic conditions in California especially as related to accumulations of the stratigraphic type leads him to conclude that estimation of ownership of oil in place with sufficient accuracy to satisfy legal standards or engineering requirements can not be accomplished before fields are entirely developed. Though not fully agreeing with Porter's conclusion even though it be conceded to be correct at the present time, the writer still sees nothing in the many examples and arguments cited that precludes a wider well spacing for that type of accumulation or that requires an exact knowledge of reservoir conditions in all its details in order to design a suitable well spacing early in the life of a field. The examples

[11] William W. Porter, II, "Geological Limitations to Oil Law," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 22, No. 5 (May, 1938), pp. 565–73.

of widely varying potentials given are not at all convincing since many workers[12] do not consider potentials a very conclusive measure of either oil in place or of reservoir conditions. In any event, even these large differences in local permeability, unless actual dry spots occur within the limits of the reservoir, have little bearing on the well-spacing problem.

In estimating reserves or ultimate recoveries of leases, the geologist who now so frequently asks, "What will be the well spacing?" before arriving at an answer, will in the future ask, "At what rate will the field be produced? Will the withdrawals under the proration plan for the field be ratable? Will gas-oil ratios be kept low through most of the flowing life of the field?" In other words, he will recognize that well density is not important in determining ultimate recovery, but that producing conditions and practices are.

A note of warning must be sounded concerning wide spacing which the geologist as adviser to the operator should heed. Spacing recommended for present producing conditions may be found entirely inadequate if, because of increased demand or changed economic conditions, pools and wells which should be produced at restricted rates are changed to open-flow or nearly open-flow rates. With such change for many types of reservoirs and accumulations more wells will be needed to accomplish the same degree of drainage that would have resulted with fewer wells under restricted flow.

Instead of the often heard dictum, "more wells, more oil," which was not even entirely true for the old open-flow conditions, the more modern counterpart will be "the more inefficiency, the more wells needed." "Inefficiency" is meant to include improper use of reservoir energy through incorrect rates of flow, unnecessarily large gas-oil ratios, and trapping of oil by uneven withdrawals.

By increasing undeveloped reserves which may be drawn upon when demand increases, the need of inefficient depletion of present producing fields is avoided, and in accomplishing this objective the geologist once again has an important place in the well-spacing problem.

Acknowledgment is expressed to the writer's fellow members on the Special Study Committee on Well Spacing of the American Petroleum Institute and to its chairman, M. Albertson, for their help in clarifying the engineering concepts involved in the well-spacing problem. The writer also wishes to thank The Atlantic Refining Company for permission to publish this paper, emphasizing that opinions expressed herein are his own and not necessarily subscribed to by officials or co-workers within that organization.

[12] "Essential Engineering Factors in the Allocation of Production, Revised Progress Report of the Topical Committee on the Allocation of Production" (revised, November, 1934, Amer. Petrol. Inst.).

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GEOLOGICAL NOTES

UNEXPOSED SILURIAN SECTION AND PRODUCING ZONE OF IRVINE OIL FIELD, ESTILL COUNTY, KENTUCKY[1]

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Lexington, Kentucky

In the past few years the Petroleum Exploration Company of Lexington, Kentucky, has undertaken the drilling of a series of core holes in the old Irvine field as a necessary preliminary step in its program of repressuring. It has made possible some study of the unexposed limestone section underlying the Ohio shale (including probably the Olentangy) and the identification of these producing beds which are unknown in outcrop on the east side of the Cincinnati arch in Kentucky.

In the outcrop near Irvine, 7–20 feet of the Boyle limestone intervene between the Ohio shale and the Crab Orchard series. Eastward the limestone section occupying this interval thickens within a few miles to 80–100 feet in the Irvine oil pool and vicinity, and to 500–600 feet in Lawrence County about 70 miles east of the outcrop. There have been few facts available to help in interpreting this section. At Cumberland Gap, where the horizon crops out, the Clinton is overlain by the Chattanooga (in part Ohio) shale. At Big Stone Gap, Virginia, limestones of Cayugan, Helderberg, and probably Onondaga age occupy the interval. In Ohio, limestones of Clinton, Niagara, and Cayugan age occur.

In 1933, Jones and the writer,[3] in their report on the Big Sinking pool a few miles southeast, interpreted a marked isopach "low" (Fig. 2) drawn on this limestone sequence ("Corniferous") as indicating a truncated pre-Ohio anticline, thus explaining the occurrence of a whole group of pools including the Irvine, Big Sinking, Ashley, Ross Creek, and others. The term "Corniferous," as used by the driller, refers to the limestone immediately underlying the "Black shale." Where several "pays" were recognized, the highest was designated "Corniferous," some of the lower ones "Niagara."

[1] Manuscript received, July 14, 1938.

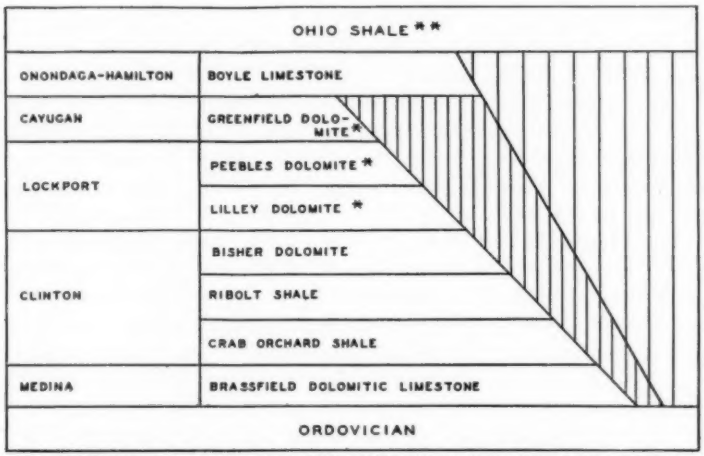
[2] Department of Geology, University of Kentucky. The writer is indebted to Walter H. Bucher, W. H. Shideler, and L. G. Westgate for information concerning the Silurian section of southern Ohio.

[3] D. J. Jones and Arthur C. McFarlan, "Geology of the Big Sinking Pool, Lee County, Kentucky," *Univ. Kentucky Bur. Min. Top. Survey Bull. 1* (1933).

The study of these four cores leads to the following conclusions.

1. The earlier inferred pre-Ohio anticline is verified.

2. The Boyle limestone, present at the outcrop, is not present, hence does not produce, in the Irvine field. Its absence is due to truncation of the buried structure. It may be present and perhaps productive in the shallow field around Ravenna nearer outcrop. Presumably it constitutes a part of the section on the eastern flank of this anticline. Whether actually productive or not is not known.



** INCLUDING GRAY SHALE NEAR BASE ("FIRE CLAY") AND A FEW FEET OF BROWN SHALE BELOW ("COFFEE SHALE") -- PROBABLY OLENTANGY.

* NOT KNOWN IN OUTCROP IN KENTUCKY.

FIG. 1.—Chart showing, by vertical lines, overlapping unconformable relationship of Boyle limestone and Ohio shale.

3. Within 5 miles between the outcrop and the Simp Horn and Tyree wells (Fig. 2), not only has the Boyle limestone been eliminated, but there has been introduced below an increasing thickness of mid-Silurian limestone, much of which has been cut through near the crest of the structure. These limestones include the Peebles, Lilley, and probably Bisher formations.

4. The productive section in the Irvine pool is Silurian and includes the Peebles as the main producer and the Lilley below. Both are Niagara and both dolomitic limestones. Neither is known in outcrop in Kentucky but both are well developed in Highland[4] and Adams counties, Ohio. The Peebles is fine-grained, hard, gray dolo-

[4] James K. Rogers, "Geology of Highland County, Ohio," *Ohio Geol. Survey Bull.* 38 (1936), 4th Ser., p. 148.

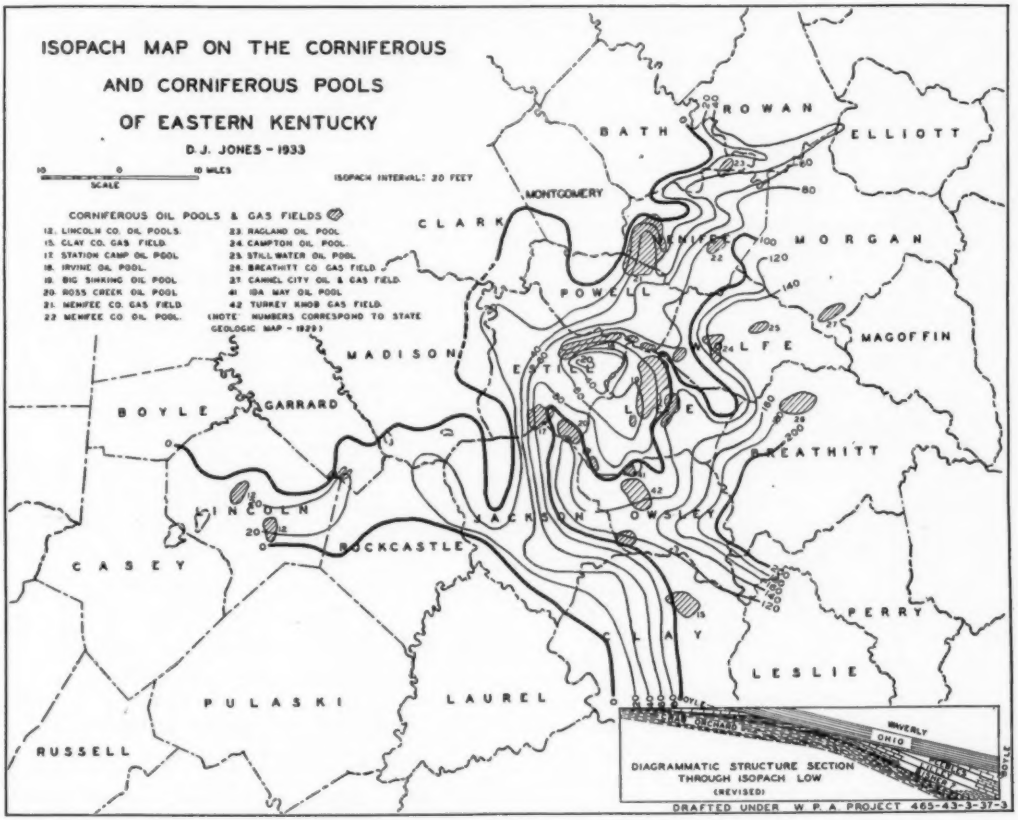


FIG. 2.—Isopach map drawn on "Corniferous." Diagonal shading shows "Corniferous" pools of eastern Kentucky.

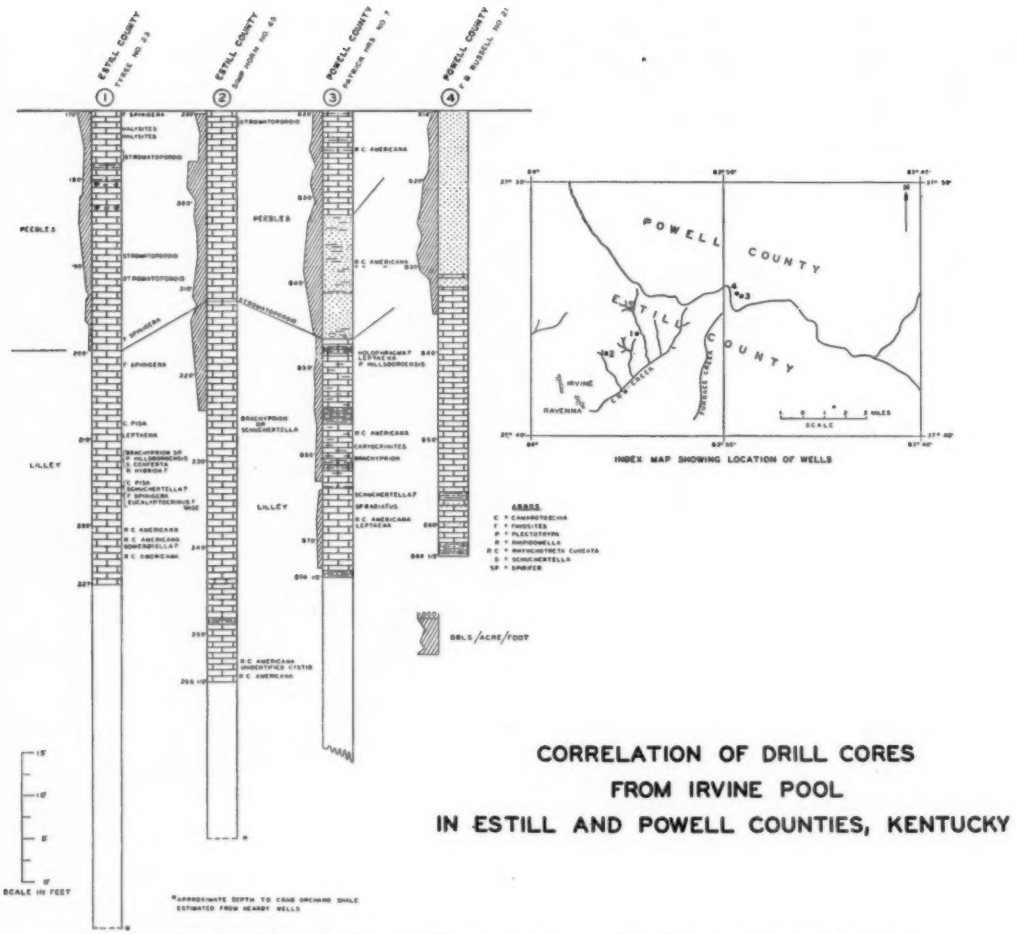


FIG. 3.—Chart showing correlation of drill cores, Irvine pool, Estill and Powell counties, Kentucky.

mite. A rather characteristic feature is a texture involving an irregular, patchy distribution of fine to dense and coarser-grained areas, the whole somewhat fractured and irregularly broken. The oil is held mainly in these coarse-grained patches, the fractures, and cavities formed by the leaching of fossils. The Lilley is medium to coarse-grained, rather soft, gray dolomite with an abundant development of very porous crinoidal limestone.

The identification of these two Niagara dolomites is made on lithologic character and fossils. The latter are the ordinary dolomitic molds. Those which could be identified with some assurance are shown in Figure 3. As indicated, *Halysites* occurs within 2 feet of the "Black shale" in the Tyree well. Small horn corals suggesting *Holophragma* occur at the top of the Lilley in the Patrick well. This is the horizon of the *Holophragma calceoides* zone in southern Ohio.

5. To date none of these core holes has penetrated to the Crab Orchard shales. It is probable that the part of the limestone section uncored (Fig. 3) is Bisher. This fine-grained dolomite is known in outcrop as far south as Fleming County, Kentucky (Foerste, 1931, p. 190; 1935, p. 141).[5]

6. The calcareous sandstone in the Patrick Heirs No. 7 is an eastern facies of the Peebles which is also shown in the Russell No. 21. Since the two show approximately the same thickness it is probable that the absence of the overlying limestone in the Russell well is a matter of unconformity. This sandstone occupies about the position of the Big Six sandstone "pay" of Breathitt County and may well be the western edge of that sandstone.

7. The increasing thickness of limestones beneath the Ohio shale eastward may explain the occurrence of "Corniferous" production only in the region bordering the outcrop. As the beds introduced involve Cayugan, Helderberg, and Onondaga, the increasing thickness of rock between the "Black shale" series and the Peebles and Lilley ("Irvine sand") may have effectually blocked migration into these beds. Of course somewhere in this eastern region the Niagaran dolomites disappear from the section.

Attention is called to the two small east-west isopach "lows" on the southern flanks of which the old Ragland (Bath County) oil pool and Menifee gas field are located. The situation in these two fields seems like that of the Irvine-Big Sinking field on a small scale.

[5] A. F. Foerste, "Paleontology of Kentucky (Silurian)," *Kentucky Geol. Survey*, Ser. 6, Vol. 36 (1931), pp. 167–215.
———, "Correlation of Silurian Formations in Southwestern Ohio, Southeastern Indiana, Kentucky, and Western Tennessee," *Dennison Univ. Bull., Jour. of the Scientific Laboratories*, Vol. 30 (August, 1935), pp. 119-205.

SOURCE OF "CORNIFEROUS" OIL IN EASTERN KENTUCKY[1]

RALPH N. THOMAS[2]
Ashland, Kentucky

Since the discovery of oil in the "Corniferous" of eastern Kentucky, attempts have been made to explain the distribution and spotted nature of producing areas. Some have explained it by areas of greater and lower porosity and permeability. Others have shown that structures, some of them pre-Ohio shale structures,[3] are the cause of accumulation.

Although these factors are important and, in most producing areas solve the problem, they do not represent the complete picture. In considerable areas wells have been drilled to the "Corniferous" that find both porosity and suitable trap, yet do not produce oil in commercial quantities. An example of this is found in the Isonville pool of Elliott County, where a dome produces a small amount of gas from the highest part of the structure, whereas drilling lower on the flank yields a strong flow of salt water but no oil.

Most authors that have dealt with this problem have considered the Ohio black shale as the source rock. It is petroliferous and possesses the characteristics of such source rocks. Oil seeps are known on the outcrop of the black shale, and some sandy shale lenses[4] within the black shale have produced oil in commercial quantities. Also, it is the major gas-producing horizon of eastern Kentucky.

In the lower part of the Black shale series is a white shale ("fire clay" of the drillers) that is widespread in eastern Kentucky. This is underlain in some areas by 10–20 feet of brown shale ("Coffee shale" of the drillers). This white shale is similar to that known on the outcrop in Ohio as the Olentangy and was provisionally correlated with that formation by Foerste.[5] It ranges from a few feet, at those places where it is exposed on the outcrop, to more than 100 feet, as shown by

[1] Manuscript received, August 5, 1938. "Corniferous" is loosely used by drillers to refer to the limestone underlying the Devonian shales, and it may be either Onondaga or Silurian.

[2] Consulting geologist. The writer is indebted to D. J. Jones and A. C. McFarlan for their help in providing data and valuable criticism, and to many Kentucky geologists who contributed useful data.

[3] D. J. Jones and Arthur C. McFarlan, "Geology of the Big Sinking Pool, Lee County, Kentucky," *Univ. Kentucky Bur. Min. Top. Survey Bull.* 1 (1933).

[4] Gordon sands. Stray sandy shale lenses occurring within the Ohio black shale series and which produce oil in Boyd County and vicinity.

[5] A. F. Foerste, "Silurian, Devonian, and Irvine Formations of East Central Kentucky," *Kentucky Geol. Survey* (1906).

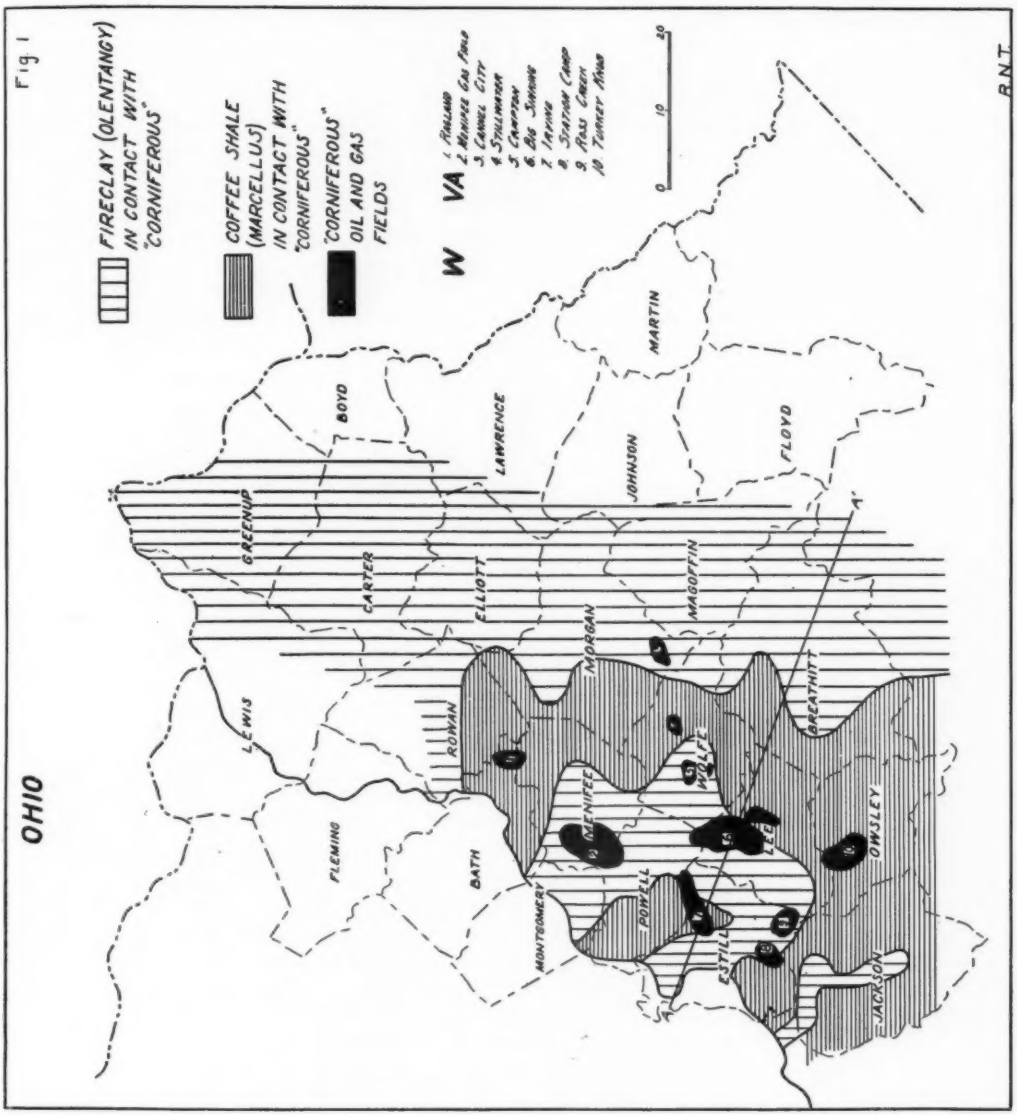


FIG. 1.—Map showing areal distribution of shales directly overlying "Corniferous."

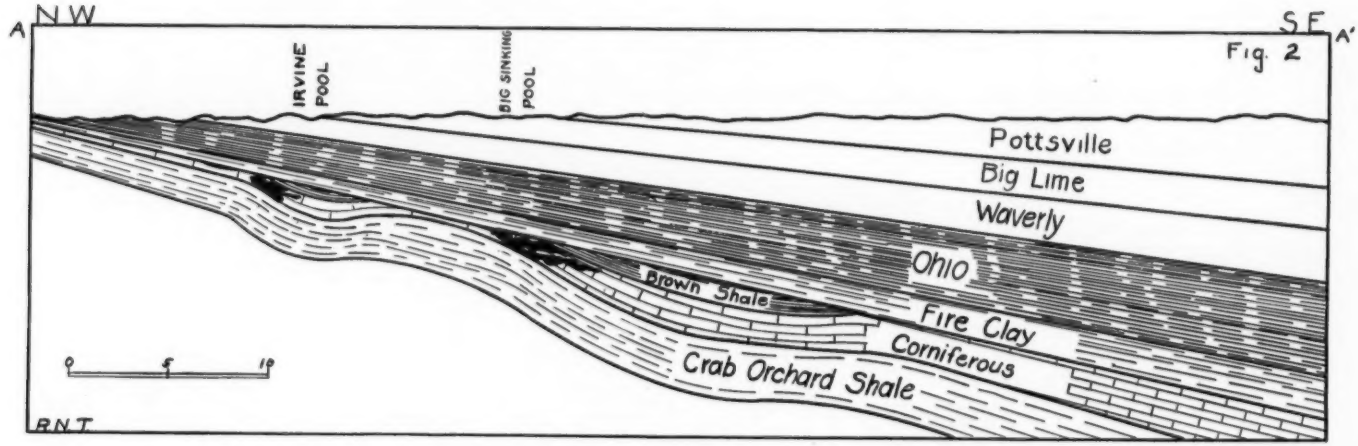


FIG. 2.—Diagrammatic representation of relationship of overlying shales to "Corniferous" along line *AA'* on Figure 1.

drill records, farther east in Carter County. In this paper the name Ohio shale is restricted to the overlying black shale and does not include the Olentangy or the underlying "Coffee shale."

White shale of this type is hardly a suitable source rock for oil but serves as a cap rock[6] to prevent the upward movement of gas and oil. It is difficult to conceive of the oil originating in the overlying Ohio black shale and passing through this impervious shale zone into the reservoir below.

It has been suggested[7] that the "Corniferous" is its own source rock, that is, the organic material was deposited with the sediments that made up the original rock. Since, in this district, there is an unconformity at the top of the "Corniferous" indicating exposure and erosion with the resulting loss of organic material by oxidization or decomposition, this seems unlikely.

Below the "Corniferous" are the blue-green Silurian shales that are low in carbonaceous material and seem unlikely to be the source rocks. The brown "Coffee shale," however, is available, and directly overlies the "Corniferous" in some localities (Fig. 2). These lenses of brown shale are similar in character to the Ohio shale but have a lighter shade of brown indicating possibly that they have been drained of part of their organic content to form the "Corniferous" oils.

A pertinent fact is their occurrence with respect to the location of the producing fields. This is shown in Figure 1. "Corniferous" production seems to be concentrated in the areas where the brown shale occurs and either overlies production or is downdip from it. It is noteworthy that east and north of the brown shale areas, where the white shale lies in contact with the "Corniferous," "Corniferous" production is lacking.

This evidence seems to indicate the "Coffee shale" as the source rock. However, in places the brown shale is absent in a producing pool; here the oil, after passing from the source rock into the reservoir, has migrated into the trap in which it is now found. The trap, due to structure, sealed unconformity, or zoned porosity, is sealed above by either the white or brown shale.

In this same connection it may be pointed out that the only area in Kentucky that produces from Ordovician limestones is in the southern part of the state where the black shale series rests directly on the Ordovician limestones without intervening white shales.

Conclusions.—That the main body of the Ohio shale is not the

[6] E. W. Shaw, "The Irvine Oil Field, Estill County, Kentucky," *U. S. Geol. Survey Bull. 661.*

[7] Jones and McFarlan, *op. cit.*

source rock of "Corniferous" oil is indicated by the presence, between this shale and the "Corniferous" reservoir, of an impervious white shale that would prevent such migration of the oil from the shale into the reservoir. The source of the oil in the "Corniferous" fields of eastern Kentucky is the brown "Coffee shale" which is in contact with the "Corniferous." The occurrence of the brown "Coffee shale" seems to be a determining factor in the location of the oil fields. The large areas east and north of the area of brown "Coffee shale" occurrence do not produce from the "Corniferous," apparently because of the presence of the white shale in contact with the reservoir.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 22, NO. 10 (OCTOBER, 1938), PP. 1457–1465

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library and available to members and associates.

PETROLEUM DEVELOPMENT AND TECHNOLOGY, 1938

REVIEW BY HARRY H. POWER[1]
Austin, Texas

"Petroleum Development and Technology, 1938." By the Petroleum Division. *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 127. 744 pp., illustrated. Published by the Institute, 29 W. 39th Street, New York City. Cloth. Price, $5.00.

The annual volume for 1938 contains the papers and discussions presented before the Petroleum Division at meetings held at Los Angeles, California, October 1, 1937; Oklahoma City, Oklahoma, October 7–9, 1937; and at New York, February 14–18, 1938. A few papers are listed by title but are not included in the volume, inasmuch as prior publication was made in various technical and trade journals. The volume gives evidence of the increasingly high standards reached by the Petroleum Division in its search for advancement in petroleum technology.

Chapter I, "Production Engineering," contains several papers of interest to the geological profession. "Spacing of Oil Wells," by Lyndon L. Foley, is especially timely and approaches the spacing problem from a new angle that has merited considerable thought, particularly from the standpoint of corrective measures to be applied to developed pools. For the geologist appraising oil pools, O. P. Gregory's paper, "Gas Caps, Their Determination and Significance," should be of considerable help in estimating oil content and assigning relative values to properties of varying structural position. The paper, "Excessive Pressures and Pressure Variations with Depth of Petroleum Reservoirs in the Gulf Coast Region of Texas and Louisiana," by G. E. Cannon and R. C. Craze, introduces the possible cause of erratic pressure below critical depths as weight of overburden and resulting compaction, a subject of considerable interest to geologists. "Pressure Drilling Operations in Kettleman Hills, and Effect on Initial Production Rates," by Read Winterburn, and "Some Considerations in Selection and Installation of Gravel Pack for Oil Wells," by C. J. Coberly and E. M. Wagner, are titles to papers of interest from the standpoints of completion practices resulting in efficient production of oil with minimum restriction to flow.

Chapter II, "Review of Notable New California Fields," includes papers on the Wilmington, El Segundo, and Ten Section fields. This chapter suggests that reviews of prominent new fields in other states may be advisable in future volumes.

Chapter III, "Engineering Research," contains papers of outstanding merit and well worth the price of the volume. "Orign of Petroleum," by E. Berl is written by a scientist having a background of many years experience in

[1] Department of Petroleum Engineering, University of Texas. Manuscript received, July 16, 1938.

research abroad and in the United States. "Pressure Distribution in Oil and Gas Reserves by Membrane Analogy," by Aaron J. Miles and Eugene A. Stephenson, presents an analogy whereby the pressure distribution in a system involving multiple wells can be easily discerned. Geologists have used various methods for estimating gas reserves, but D. T. MacRoberts has applied fundamentals to the problem in his paper, "Relation of Gas-Well Spacing to Ultimate Recovery," to the ultimate profit of geologists and engineers interested in the most scientific approach possible. Donald L. Katz, Stuart E. Buckley, and Eugene A. Stephenson have contributed significantly in their respective papers, "Application of Vaporization Equilibrium Constants to Production Engineering Problems," "Calculation of Equilibrium in Hydrocarbon Mixtures," and "Behavior of Contents of High-pressure Reservoirs." With the trend of deep production toward the so-called "distillate wells," the significance to the geologist is obvious.

"Connate Water in Oil and Gas Sands," by Ralph J. Schilthuis, and "Influence of Connate Water on Permeability of Sands to Oil," by Eldon N. Dunlap, also bear on the problem of oil recovery and appraisal, and therefore are of fundamental interest to the geologist. Several excellent papers on drilling muds, such as Charles E. Reed's, "Recent Advances in Knowledge of Colloidal Properties of Clay Suspensions and Gels," are of secondary interest, perhaps, to the geologist and furnish a striking example of the advancement in application of fundamentals to drilling problems.

Chapter IV, "Petroleum Economics," has for its initial paper, the annual classic of Joseph E. Pogue. The present subject is "An Equilibrium Theory of Proration." Geologists often find time to consider oil shares and should profit by reading, "Market Behavior of Oil Shares for 1932 to 1937," by Norman D. Fitzgerald. Finally, on the basis that the profession has become increasingly conscious of the broader phases of oil economics, the papers by V. R. Garfias, R. V. Whetsel, and J. W. Ristori on "World Consumption of Petroleum Products and Related Fuels," should be particularly instructive.

Chapter V, "Production," contains 55 papers, 386 pages, on domestic and foreign production. Statistics for the more important fields are presented. This section is continuous from year to year and has been found in many cases to be an indispensable source of information.

Chapter VI, "Refining," contains one paper, "Review of Refinery Engineering for 1937," by Walter Miller.

A complete set of "Petroleum Development and Technology," A.I.M.-M.E., should occupy a prominent place in the petroleum geologist's library.

ORIGIN OF THE SHOESTRING SANDS OF GREENWOOD AND BUTLER COUNTIES, KANSAS, BY N. WOOD BASS

REVIEW BY J. L. GARLOUGH[1]
Wichita, Kansas

"Origin of the Shoestring Sands of Greenwood and Butler Counties, Kansas." By N. Wood Bass. *State Geol. Survey of Kansas Bull. 23* (1938). Investigation conducted under a coöperative agreement with the United States Geological Survey. 135 pp., 10 figs., 21 pls. Paper. 6×9 inches. Price, $0.25.

[1] Consulting geologist. Manuscript received, July 23, 1938.

The origin of the shoestring sands of Greenwood and Butler counties, in southeastern Kansas, has long been a mooted question. It was only subsequent to the development of the numerous oil fields in the area that sufficient data were at hand on which to base a comprehensive study of the problem. During the years 1931–1934 such a study was made by N. W. Bass. It was primarily confined to northern Greenwood County and the immediately adjacent parts of bordering counties. Later a separate investigation was conducted in Osage County, Oklahoma, and Cowley County, Kansas, which adjoins it.

The shoestring sands occur in the lower part of the Cherokee shale which is the lowermost unit of the Pennsylvanian series in Kansas. They lie at depths ranging from 1,500 to 2,800 feet. Their width varies from 0.5 to 1.5 miles and their length may be several times as great. In thickness they average about 50 feet. They have typical linear arrangements which have popularly been termed "trends." The maximum length of a trend is 50 miles. Two of them extending northeast and southwest have been called "main trends," probably because of priority of discovery. Two others extending northwest and southeast, almost at right angles to the main trends, have been called "cross trends." A fifth trend, extending approximately north and south, occurs some distance southwest of the others. The main trends are located about 15 miles east of the Nemaha granite ridge at the nearest points and approximately parallel it. This ridge was a positive element during early Cherokee time.

It had commonly been recognized by Kansas geologists that the sand bodies are not reflected by the attitude of the surface rocks. Extremely detailed mapping of three of the shoestring-sand oil pools and compilation of surface structure maps of the whole district corroborated this belief. The conformity at some localities is probably incidental and not a reflection of the mass of the sand body due to differential compaction in the overlying sediments.

A detailed discussion sets forth under appropriate headings the factual information collected during the course of the investigation. The sources of data necessarily were limited to the logs of oil wells and dry holes in the area, and to the drill cuttings, cores, and shot fragments saved from them. Approximately 5,000 well records were used.

Review of the various means by which sandstone may be deposited and careful examination of all the evidence obtainable convinced the author that these shoestring sands were formed as offshore bars. Their deposition took place along a low swampy shore in a broad embayment on the western margin of a sea which occupied much of eastern Kansas and Oklahoma during Cherokee time. The four principal trends compose two bar systems each consisting of one main trend and one cross trend. The systems of bars were built at slightly different stages during a southeastward retreat of the sea caused by uplift in the Nemaha granite ridge region on the northwest. Correlations between parallel trends and the stratigraphic relationship of the sands at one point of intersection tend to substantiate their two stage development. Due to the fact that the main and cross trends lie nearly at right angles to each other it is necessary to assume the existence of a land area forming the northeast side of the embayment. However, isopach studies of the Cherokee shale and older formations support such an hypothesis.

Since shore features are constantly changing and offshore bars are es-

pecially subject to destruction, the possible manner of their preservation is important. Observations made along parts of the Atlantic coast have revealed old bars in process of submergence in the lagoonal muds back of more newly formed bars. Thus it appears that bars can be preserved on low swampy coast lines under favorable conditions.

Data bearing on the origin of the oil contained in the sand lenses indicate that it was not widely disseminated through the enclosing shale, but that it was formed in the sediments immediately adjacent to the sands and at the same stratigraphic horizon. Conditions in this narrow zone at the time of sand deposition and submergence should have been ideal for the growth of probable oil-forming organisms.

The report contains copious references. Its illustrations are numerous and excellent. Particular mention should be made of the block diagrams showing the shapes of the individual sand bodies for these are major points of evidence. There are hypothetical sketches of the Cherokee sea during the two stages of bar building. A very pertinent illustration gives a direct comparison of a part of one of the shoestring-sand trends with a segment of the present bar system on the New Jersey coast.

Determination of the origin of these shoestring sands presents a difficult problem of research in sedimentation. The author has carried out his investigation of them in an able and thorough manner. His logical interpretations are not only of scientific interest but may also find economic adaptation in any area where similar sand deposits occur.

BIBLIOGRAPHY OF WEST INDIAN GEOLOGY
BY L. M. R. RUTTEN

REVIEW BY R. D. REED[1]
Los Angeles, California

"Bibliography of West Indian Geology." By L. M. R. Rutten. *Physiographisch-geologische Reeks No. 16*. N. V. A. Oosthoek's Uitgevers-Mij., Utrecht (1938). vii+103 pp.

In consequence of studies which he began in 1921, and particularly of those made in 1930 and 1931 in connection with the giving of some lectures on the West Indies in the University of Utrecht, Professor Rutten has been suffering from an "obsession" with reference to the collection of a complete bibliography of West Indian geology. In the hope of securing relief he has finally decided to publish the data in his possession. Since he hints at the possibility of issuing a second bibliography "in the distant future," it would seem that he has little faith in the remedy; possibly he hopes that his labors may be easier and his results more complete if a wider circle of colleagues knows that they are in progress.

Whatever the result of this publication may prove to be with regard to Professor Rutten's difficulty, he has here collected 2,434 titles, has distinguished by an asterisk those he has been unable to see, and has provided an index. This service should be of the utmost value to all geologists who for any reason become dissatisfied with their knowledge of West Indian geology.

[1] The Texas Company. Manuscript received, August 22, 1938.

It shows at a glance that the task of reading everything on the subject is perhaps ten or twenty times as great as most of us would have guessed, but this possible disservice is abundantly offset by the convenience of having the unsuspected riches so well organized and conveniently listed.

In connection with the possible future issue of another bibliography Professor Rutten hopes that his colleagues will see to it that he gets as complete information as possible on the publications omitted from the present list and on those that may appear in the future. "All hints should be directed to the Geological Institute of the University of Utrecht, Netherlands; 320 Oude Gracht."

RECENT PUBLICATIONS

ARGENTINA

*"Observaciones Geológicas en el Oeste de Santa Cruz (Patagonia)" (Geological Observations in Western Santa Cruz, Patagonia), by Alejandro Piatnizky. *Bol. Inform. Petroleras* (Buenos Aires), Vol. 15, No. 165 (May, 1938), pp. 45–95; 16 figs., 10 pls. illustrating fossils.

BRAZIL

*"Relatorio da Directoria, 1934–1935," by Avelino Ignacio de Oliveira. *Serviço de Fomento da Producção Mineral Bol. 18* (Rio de Janeiro, 1937). Director's administrative report, including "Bituminous Shales," pp. 112–18, and "Petroleum," pp. 119–31 and 2 maps. 199 pp., many illus. Portuguese.

*"Iniciação ao estudo das formações Carboniferas do Sul do Brasil" (Carboniferous Formations of Southern Brazil), by José Fiuza da Rocha. *Ibid., Avulso 25* (1938). 14 pp. Reprinted from *Mineração e Metallurgia*, No. 10 (November-December, 1937).

*"Dificuldades específicas em pesquisa de Petróleo no Sul do Brasil" (Difficulties of Petroleum Exploration in Southern Brazil), by Glycon de Paiva Teixeira. *Mineração e Metallurgia* (Rio de Janeiro), Vol. 3, No. 13 (May-June, 1938), pp. 50–52, 1 geological map.

*"Folhelho pirobetuminoso de Sao Gabriel R. G. do Sul" (Bituminous Shale of Sao Gabriel, Rio Grande do Sul), by Emilio Alves Teixeira. *Ibid.*, pp. 53–54; 2 figs.

CALIFORNIA

"Geologic Map of California," *California Division of Mines* (San Francisco, 1938). 7×7 feet, 6 sheets. Price, $4.00. Made with 10 color plates. Shows culture, streams, roads, and approximately 80 geological units, with smaller maps showing submarine contours, source data, mineral locations, rainfall, glacial features, and a geologic time scale based on data from radioactivity.

"Pliocene Diatoms from the Kettleman Hills, California," by K. E. Lohman. *U. S. Geol. Survey Prof. Paper 189-C* (1938), pp. i–ii, 81–102, Pls. 20–23. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.15.

"Lower Pliocene Mollusks and Echinoids from the Los Angeles Basin, California, and Their Inferred Environment," by W. P. Woodring. *Ibid., Prof. Paper 190* (1938). 67 pp., 9 pls., 2 figs. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.30.

CZECHOSLOVAKIA

"Die stratigraphischen und tektonischen Grundlagen der Erdöllagerstätten im Neogen von Südmähren und der Slowakei" (The Stratigraphic and Tectonic Basis of the Petroleum Deposits in the Neogene of Southern Moravia and of Slovakia), by L. Sommermeier. *Petroleum*, Vol. 34, No. 5 (1938), pp. 1 ff.; 3 figs. *Review in *Kali und Erdöl* (Berlin), Jahrg. 32, Heft 16 (August 15, 1938), p. 175.

GENERAL

*"The Application of Physico-Chemical Principles to the Investigation of the Properties of Rocks:—Part I. Porosity—Origin, Significance and Measurement," by A. H. Nissan. "Part II. Apparatus and Technique for Porosity Measurement," by A. H. Nissan, C. E. Wood, L. V. W. Clark, and A. W. Nash. *Jour. Inst. Petrol. Tech.* (London), Vol. 24, No. 177 (July, 1938), pp. 351–70. Part I contains 8 figs., 2 tables. Part II contains 9 figs., 11 tables.

*"Sediment-Heft" (Symposium on Sediments). *Geol. Rundshau* (Stuttgart), Bd. 29, Heft 3–5 (July, 1938). 461 pp., 79 figs., 22 articles by 20 authors, in 8 parts: I. "Grundsätze und Methoden" (Principles and Methods); II. "Die Tone" (The Clays); III. "Niederlande, Nord- und Ostsee" (Lowlands, North and East Sea); IV. "Tiefsee" (Deep Sea); V. "Festland" (Continent); VI. "Ältere Sedimente" (Ancient Sediments); VII. "Böden- und Erdbau" (Soil and Soil Building); VIII. "Nutzbare Sedimente" (Economic Sediments).

"Species and Genera of Tertiary Noetinae," by F. S. MacNeil. *U. S. Geol. Survey Prof. Paper 189-A* (1938), pp. i–ii, 1–49, Pls. 1–6, Figs. 1–2. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.20.

*"Key to Papers Published by an Institute for the Study of Modern Sediments in Shallow Seas," by Walter H. Bucher. *Jour. Geol.* (Chicago), Vol. 46, No. 5 (July–August, 1938), pp. 726–55; 6 figs.

*"Practical Problems in Oil Exploration," by Gerald H. Westby. *Oil and Gas Jour.* (Tulsa), Vol. 37, No. 15 (August 25, 1938), p. 39.

*"United States Magnetic Tables and Magnetic Charts for 1935," by H. Herbert Howe and David G. Knapp. *U. S. Coast and Geodetic Survey Serial 602* (1938). 161 pp. 6×9¼ inches. Paper. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.60.

*"Voraussetzungen und Grenzen der Mikropaläontologie" (Assumptions and Limitations of Micropaleontology), by Ernst E. Hensoldt. *Petrol. Zeit.* (Vienna), Jahrg. 34, Nr. 31 (August 3, 1938), pp. 8–9.

*"Mikropaläontologie und Praxis" (Micropaleontology and Practice), by C. A. Wicher. *Ibid.*, p. 10.

*"Voraussetzungen und Grenzen der Micropaläontologie" (Assumptions and Limitations of Micropaleontology), by Ernst E. Hensoldt. *Zeit. f. Prakt. Geol.* (Halle), Jahr. 46, Heft 7 (July, 1938), pp. 133–34. The wording of this article is not the same as that of the foregoing article with the same title.

*"Ozarkian and Canadian Brachiopoda," by E. O. Ulrich and G. Arthur Cooper. *Geol. Soc. America Spec. Paper 13* (August 22, 1938). 323 pp., 14 figs., 58 pls. Contains 1 correlation chart.

*"Die Metamorphose ozeaner Salzablagerungen" (The Metamorphism of Ocean Salt Deposits), by Hermann Borchert. *Kali und Erdol* (Berlin), Jahrg. 32, Heft 16 (August 15, 1938), pp. 169–72.

*"Heliumlagerstätten" (Helium Deposits), by Rudolf Wager. *Ibid.*, pp. 173–75; 1 fig., 1 table.

**About Petroleum*, by J. G. Crowther. 181 pp., 15 pls. Approx. 5½×8½ inches. Cloth. Oxford University Press, London and New York (1938). Price, $2.25.

*"Devonian Ammonoids of America," by A. K. Miller. *Geol. Soc. America Spec. Paper 14* (August 31, 1938). 262 pp., 41 figs., 39 pls., 2 tables.

GEOPHYSICS

"Geophysical Abstracts 90, July–September 1937," by W. Ayvazoglou. *U. S. Geol. Survey Bull. 895-C* (1938), pp. i–ii, 93–136. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.10.

GERMANY

*"Zur Kenntnis des tiefsten Schliers in Oberdonau" (On the Knowledge of the Deepest Schliers in the Upper Danube), by Gustav Götzinger. *Petrol. Zeit.* (Vienna), Jahrg. 34, Nr. 31 (August 3, 1938), pp. 1–3.

*"Die Foraminiferenfauna des süddeutschen Dogger-Deltas" (The Foraminiferal Fauna of the South German Dogger Deltas), by Oskar Kuhn. *Ibid.*, pp. 3–7; 1 pl. with 22 figs. of Foraminifera.

ILLINOIS

*"Geologist Has Optimistic View of Oil Possibilities in Illinois," by Dorsey Hager. *Oil and Gas Jour.* (Tulsa), Vol. 37, No. 13 (August 11, 1938), p. 25; 1 map.

"Oil and Gas Development Map of the Centralia, Illinois, Area." *State Geol. Survey Illinois* (Urbana, 1938). "Shows towns, main roads (also minor roads in developed areas), section, township, and county lines; well locations, rigs, and drilling wells; and oil, gas, dry, and abandoned wells. The scale is 2 inches equals 1 mile (1–31,680)." This is the first of a series of development maps that will be brought up to date as often as new data warrant. Order from Enid Townley, Map Agent, 305 Ceramics Building, Urbana. Price, $0.60.

*"Kankakee Arch in Illinois," by George E. Ekblaw. *Bull. Geol. Soc. America* (Washington), Vol. 49, No. 9 (September 1, 1938), pp. 1425–30; 1 fig.

KANSAS, IOWA, MISSOURI

*"The Forest City Basin, A Comparison With the Illinois Basin," by W. G. Osborn. *Oil and Gas Jour.* (Tulsa), Vol. 37, No. 13 (August 11, 1938), pp. 27–29, 34; 5 figs., including 4 cross sections.

NEBRASKA

*"The Bearing of the Valentine Area in Continental Miocene-Pliocene Correlation," by Paul O. McGrew and Grayson E. Meade. *Amer. Jour. Sci.*, Vol. 36, No. 213 (September, 1938), pp. 197–207; 1 chart.

*"Commentary on McGrew and Meade's Paper," by G. Edward Lewis. *Ibid.*, pp. 208–11.

*"Remarks on the Use of the Name 'Valentine'," by Edwin H. Colbert. *Ibid.*, pp. 212–14.

*"Further Comments on the Usage of 'Valentine'," by F. Walker Johnson. *Ibid.*, pp. 215–19.

*"The Nebraska State Geological Survey and the 'Valentine Problem'," by A. L. Lugn. *Ibid.*, pp. 220–27.

NEW YORK

"Geologic Structure and Occurrence of Gas in Part of Southwestern New York," Pt. 1, "Structure and Gas Possibilities of the Oriskany Sandstone in Steuben, Yates, and Parts of the Adjacent Counties," by W. H. Bradley and J. F. Pepper, *U. S. Geol. Survey Bull. 899-A* (1938), pp. i–iv, 1–68, Pls. 1–4, Figs. 1–7. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.35.

OKLAHOMA

"Geology and Fuel Resources of the Southern Part of the Oklahoma Coal Field," Pt. 3, "The Quinton-Scipio District, Pittsburg, Haskell, and Latimer Counties," by C. H. Dane, H. E. Rothrock, and J. S. Williams. *U. S. Geol. Survey Bull. 874-C* (1938), pp. i–iv, 151–253, Pls. 12–26, Figs. 8–11. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.65.

"Subsurface Geology and Oil and Gas Resources of Osage County, Oklahoma," Pt. 1, "Townships 22 and 23 North, Ranges 10 and 11 East," by N. W. Bass, L. E. Kennedy, W. R. Dillard, Otto Leatherock, and J. H. Hengst. *Ibid., Bull. 900-A* (1938), pp. i–iv, 1–45, Pl. 1, Fig. 1. Price, $0.30.

PERU

"Geomorphologie des Tumbesdeltas, Perú" (Geomorphology of the Tumbes Delta, Peru), by Augusto Cabrera la Rosa. Translated from Spanish by Georg Petersen. Reprint from *Geologie der Meere und Binnengewässer*, Bd. 2, Heft 1 (1938), S. 1–21; 3 black-line maps, 5 photographs.

POLAND

**Bull. Geol. Survey Poland*, Vol. 9, No. 2 (Warsaw, 1938). 234 pp., 14 figs., 8 pls. 7×10 inches. Paper cover. Contains the following articles in Polish with a summary of each in either German or French. "Fauna of the Sandstone of Golonóg," by St. Weigner; "The Nummulites of the Menilitic Schists of Seletyn (Bukowina, Roumania)," by F. Bieda; "The Erratics of the White Chalk between the Niemen and the Jasiolda (Northeast Poland)," by Zb. Sujkowski; "Stratigraphy and Tectonics of the Cretaceous Deposits in the Vicinity of Lelów," by S. Z. Różycki; "Stratigraphic Studies on the Covering of the Pienine Klippe (Polish Carpathians).—Part I. Brief Account of the Subdivision of the Covering of the Klippe," by L. Horwitz; "Some Observations on the Geology of the Surroundings of Seletyn (Bukowina)," by H. Świdzinski.

*"Geological Bibliography of Poland, No. 16, 1936," by R. Danysz-Fleszarowa. *Service Géol. de Pologne* (Warsaw, 1938). 59 pp., items 181–225 supplementing No. 15, 1935.

ROCKY MOUNTAIN REGION

*"Economics and Geology of the Rocky Mountain Area," by L. C. Uren. *World Petrol.* (New York), Vol. 9, No. 8 (August, 1938), pp. 34–49; 14 figs.,

3 tables. The first of three installments of an exhaustive study of the oil and gas fields of the Rocky Mountain area.

WYOMING

*"Porosity of the Sundance Sand in the Lance Creek Oil Field, Wyoming," by H. Dale Nichols. *U. S. Bur. Mines R. I. 3410* (July, 1938). 15 mim. pp., 4 figs., 1 table on 7 pp.

ASSOCIATION DIVISION OF PALEONTOLOGY AND MINERALOGY

**Journal of Paleontology* (Tulsa, Oklahoma), Vol. 12, No. 5 (September, 1938).

"Conodonts of the Olentangy Shale," by Clinton R. Stauffer

"New Devonian Fossils from Calhoun County, Illinois," by G. Arthur Cooper and Preston E. Cloud.

"Middle and Upper Cambrian Faunas from Western Newfoundland," by Christina Lochman

"Upper Middle Devonian Rugose Corals of the Nevada Limestone," by Erwin C. Stumm

"New Genera of Ostracoderms from the Upper Silurian of Oesel," by George R. Robertson

"Orbitoids from the Crescent Formation (Eocene) of Washington," by Sheridan A. Berthiaume

"Pennsylvanian Sponges of North-central Texas," by Ralph H. King

"New Species of Gastropoda from the Oligocene of Colorado," by Loris S. Russell

"A Stomatopod from the Mississippian of Central Montana," by Harold W. Scott

"Onondaga Paint-ore Fauna from Pennsylvania," by Bradford Willard and Lawrence Whitcomb

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 22, NO. 10 (OCTOBER, 1938), PP. 1466-1468

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to the Executive Committee, Box 979, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

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TWENTY-FOURTH ANNUAL MEETING, OKLAHOMA CITY MARCH 22–24, 1939

Headquarters for the twenty-fourth annual meeting of the Association at Oklahoma City, March 22–24, 1939, is to be the Biltmore Hotel, where the seventeenth annual meeting was held in 1932. Officers headquarters and committee rooms will be in the hotel. The technical program, banquet, dance, and scientific exhibits will be held in the new municipal auditorium which is sufficiently large and conveniently arranged to accommodate not only the general sessions of the Association but also the meetings of the Society of Economic Paleontologists and Mineralogists and the Society of Exploration Geophysicists. The accessibility of Oklahoma City for the majority of members and all geologists and friends in the Mid-Continent and its central location for those who will come from the far western and eastern states indicate an attendance that will set a high mark in Association records. The combined Association attendance, divisional and affiliate, at New Orleans, last March, was approximately 2,000 persons. The total membership is now at the new high of 2,905, of whom 2,236 are active or full members and 669 are associates.

The geologists of the western district of Oklahoma, acting through the Oklahoma City Geological Society, in inviting the Association to meet in Oklahoma City have assumed a very considerable responsibility. All members and their friends who are thinking of attending this meeting should appreciate the efforts of these fellow workers, at least to the extent of planning their trip and reserving their accommodations early, so as to give the local committees and hotels ample time to make proper arrangements.

The general committee is composed of R. W. Laughlin, of Laughlin-Simmons and Company, 1320 First National Bank Building, general chairman, J. T. Richards, Gulf Oil Corporation, Box 1557, chairman of the technical program committee, and John E. Van Dall, Magnolia Petroleum Company, Box 1828, vice-chairman in charge of arrangements, all of Oklahoma City.

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 22, NO. 10 (OCTOBER, 1938), PP. 1469-1472

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

C. TAYLOR COLE is taking a 9 months leave of absence from University Lands at Midland, Texas, and will be connected with the department of geology at The University of Texas at Austin, during that time. After September 15 he may be addressed at 1616 Colorado Street, Austin, Texas.

RAY R. MOODY, Gulf Oil Corporation, has been transferred from Kansas to the office of the company's eastern division at Owensboro, Kentucky.

W. I. CUNNINGHAM has been placed in charge of the Bishop Oil Company's land and geological departments at Bakersfield, California. CARL TODD is assistant to Cunningham.

GORDON I. ATWATER, formerly with the Skelly Oil Company at Houston, is now with William Helis Company at New Orleans, Louisiana.

HENRY CARTER REA has returned from Afghanistan where he was working for the Inland Exploration Company at Kabul, and is now district geologist for the Shell Petroleum Corporation at Owensboro, Kentucky.

DWIGHT C. ROBERTS, Sperry-Sun Well Surveying Company, has been appointed regional manager of the Pacific Coast Region. He has supervision of the company's activities in all the west coast area.

BENTON R. VERNON, Mid-Continent Petroleum Corporation, has been transferred from Houston, Texas, to Shreveport, Louisiana, where his address is 323 Ardis Building.

G. LESLIE WHIPPLE has changed his address from Apartado 4, Puerto Mexico, Ver., Mexico, to Apartado Nacional No. 3, Ibague, Colombia, South America.

O. L. BRACE, consulting geologist, has returned from Greece, and has reopened his offices at 804 Second National Bank Building, Houston, Texas.

FRANK B. TAYLOR, author of many papers concerning glacial geology and the origin of continents, died on June 12, 1938, at the age of 78, after an attack of coronary thrombosis.

L. GUY HUNTLEY, formerly with the department of geology of the University of Pittsburgh, is now with the Lago Petroleum Company at Maracaibo, Venezuela.

T. J. GALBRAITH, Standard Oil Company of Texas, has changed his address from Dallas to 1500 Petroleum Building, Houston, Texas.

H. M. FRITTS, Shell Petroleum Corporation, has been transferred from St. Louis, Missouri, to Houston, Texas.

FRITZ E. VON ESTORFF has changed his address from Nederlandsche Pacific Petr. Mij., Batavia C, Java, to Socony Vacuum Oil Company, producing department, Gebouw Petrolea, The Hague, Holland.

CHESTER W. WASHBURNE, consulting geologist, may now be addressed at Room 2603, 149 Broadway, New York.

CLARENCE E. BREHM has recently accepted a position as chief geologist for the Kingwood Oil Company, and may be addressed at 327 N. Third, Effingham, Illinois.

NORVAL NICHOLS, formerly of Goldsmith, Texas, may now be addressed in care of the Humble Oil and Refining Company, Drawer Z, Hobbs, New Mexico.

JOHN L. RIDGWAY, illustrator of many scientific books, retired from active duty as scientific illustrator for the Carnegie Institution of Washington and the California Institute of Technology on July 31, 1938.

D. B. WINES, Tide Water Associated Oil Company, has been transferred from Wichita, Kansas, to Mattoon, Illinois.

E. T. MONSOUR, chief paleontologist for the Standard Oil Company of New Jersey in Mexico, resigned on July 31, 1938. He may be addressed at 1769 Lakeshore Drive, Shreveport, Louisiana.

C. M. CLARK, Indian Territory Illuminating Oil Company, has been transferred from Bartlesville, Oklahoma, to Mattoon, Illinois, where he has opened a new office for the company.

ERNEST C. ARNOLD, United States Geological Survey, has been transferred from Oklahoma City to Roswell, New Mexico. His district includes New Mexico, Arizona, and parts of Utah and Colorado.

The semi-centennial meeting of the Geological Society of America will be held at the Waldorf Astoria Hotel, New York City, on December 28–30, 1938.

CHESTER NARAMORE has accepted a position as assistant secretary of the American Institute of Mining and Metallurgical Engineers, and has automatically become executive secretary of the Petroleum Division. He assumed his duties on August 1.

THOMAS C. WILSON, formerly with the Commonwealth Gas Corporation at Pittsburgh, Pennsylvania, has accepted a position with the Atlantic Refining Company of Cuba, at Havana. He may be addressed at Room 401, Edificio La Metropolitana, Havana, Cuba.

JAMES Z. ZIMMERMAN, formerly with the Syndicate Oil Corporation at Wichita, Kansas, is now engaged in consulting work. His address is Delmont, Pennsylvania.

Mr. and Mrs. HAROLD WAYNE THOMS announce the birth of Louise Osborne Thoms on August 24, at Huntington Park, California.

E. A. RITTER, formerly with Cia de Petroleo Shell de Colombia, at Bogotá, may now be addressed in care of the Swiss Bank Corporation, Basle, Switzerland.

KENNETH R. PARSONS, formerly with The Texas Company at Denver, Colorado, is now with the Inland Exploration Company at Kabul, Afghanistan.

GEORGE R. ELLIOTT, Phillips Petroleum Company, has been transferred from the company's division office at Shreveport, Louisiana, to the production department at Bartlesville, Oklahoma.

G. H. CLARK, The Texas Company, has been transferred from San Antonio to Houston. He was replaced at San Antonio by J. M. PATTERSON, formerly of Corsicana, Texas.

RAY A. HANCOCK, the Lane-Wells Company, has returned to California from 3 months' work in Alberta, Canada, where the company has opened a new branch office. He has been transferred from Long Beach to Santa Barbara where he is in charge of the Santa Barbara district.

H. J. BUDDENHAGEN, formerly of Bakersfield, California, may now be addressed in care of the Caribbean Petroleum Company, Maracaibo, Venezuela, South America.

W. M. OSBORN, formerly with the Shell Petroleum Corporation, is now engaged in consulting geological practice. He may be addressed at Box 707, Midland, Texas.

R. L. MARSTON, formerly district superintendent for the Sun Oil Company at Forks, Washington, is now regional manager for the Sperry-Sun Well Surveying Company with headquarters at Houston, Texas.

JOHN R. SCHWABROW, United States Geological Survey, has been transferred from Casper, Wyoming, to Thermopolis, Wyoming, where he is district petroleum engineer with supervision of oil and gas operations on Federal lands in the Big Horn and Wind River basins.

IRA O. BROWN, formerly with The Ohio Oil Company as geologist and district manager for South Texas at San Antonio, has resigned. He will operate independently in San Antonio at 1011 Milam Building.

L. KEHRER has changed his address from Zehnderweg 23, Olten, Switzerland, to the Caribbean Petroleum Company, Maracaibo, Venezuela, South America.

GEORGE W. LAPEIRE, consulting geologist, has moved his headquarters from Shreveport, Louisiana, to St. Louis, Missouri.

JESSE A. ROGERS, The Texas Company, has been transferred from Roswell, New Mexico, to Wichita Falls, Texas, where he is assistant to W. D. KELLEY.

LEWIS B. KELLUM has changed his address from the Vacuum Oil Company, Wellington, New Zealand, to the New Zealand Petroleum Company, Ltd., Box 295, Gisborne, New Zealand.

C. A. RUSSELL, formerly general superintendent for the Pan American Production Company, Houston, Texas, has resigned to become engaged in business for himself.

H. G. WALTER, The Texas Company, has been transferred from Hobbs, New Mexico, to Pampa, Texas, where he is district geologist.

A. A. HOLSTON, Stanolind Oil and Gas Company, has been transferred from Tyler, Texas, to Shreveport, Louisiana, where he is in charge of the geological department of that company's new office.

PAUL D. TORREY, Sloan and Zook Company, Houston, has been appointed chairman of the subcommittee on secondary oil recovery by the American Petroleum Institute.

M. M. KORNFELD, consulting geologist, spoke before the first fall meeting of the Houston Geological Society, September 15, on "An Illustrated Discussion of the Relation of Salt Dome Faulting to Oil and Gas Accumulation."

REX M. F. TOWNSEND has changed his address from Apartado Aereo 3983, Bogota, Colombia, to Socony-Vacuum Oil Company, foreign producing department, Postbus 328, The Hague, Netherlands.

CHARLES GILL MORGAN, vice-president of the United Geophysical Company, Pasadena, California, recently made a tour of his company's operations in Trinidad.

CHARLES R. HOFFMANN has returned to his home address, 79 Grandes Arcades, Strasbourg, France, after extended field work in Lukula and Boma, Belgian Congo.

W. S. W. KEW, president of the Pacific Section of the Association, has appointed MAX L. KRUEGER as chairman of the program committee and H. D. HOBSON as chairman of the arrangements and entertainment committee for the fifteenth annual meeting of the Section at Los Angeles, California, November 3–4, 1938.

J. HARLAN JOHNSON, of the Colorado School of Mines, Golden, Colorado, spent most of the summer in Europe pursuing his studies on algal limestones.

GLEN C. THRASHER, The Texas Company, has been transferred from Wichita, Kansas, to Mattoon, Illinois.

FREDERICK J. SMITH, formerly with the Shell Petroleum Corporation, has accepted an assistant instructorship in geology at the Missouri School of Mines at Rolla, Missouri.

J. H. WHARTON, Phillips Petroleum Company, has been transferred from Amarillo to Corpus Christi, Texas.

H. H. BRADFIELD, The Texas Company, Fort Worth, Texas, spoke before the Ardmore, Oklahoma, Geological Society, September 16, on "Correlation of the Pennsylvanian of Texas and Oklahoma."

PROFESSIONAL DIRECTORY

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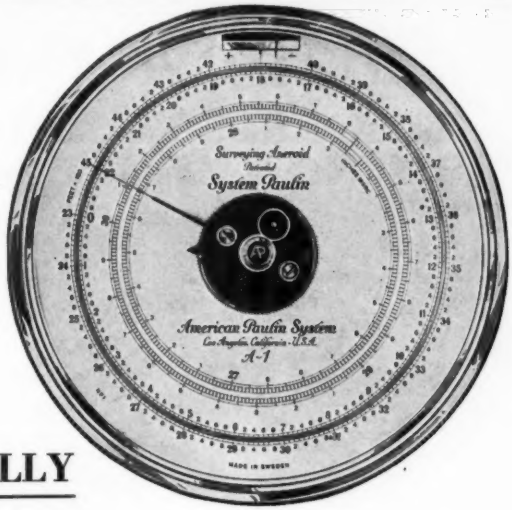

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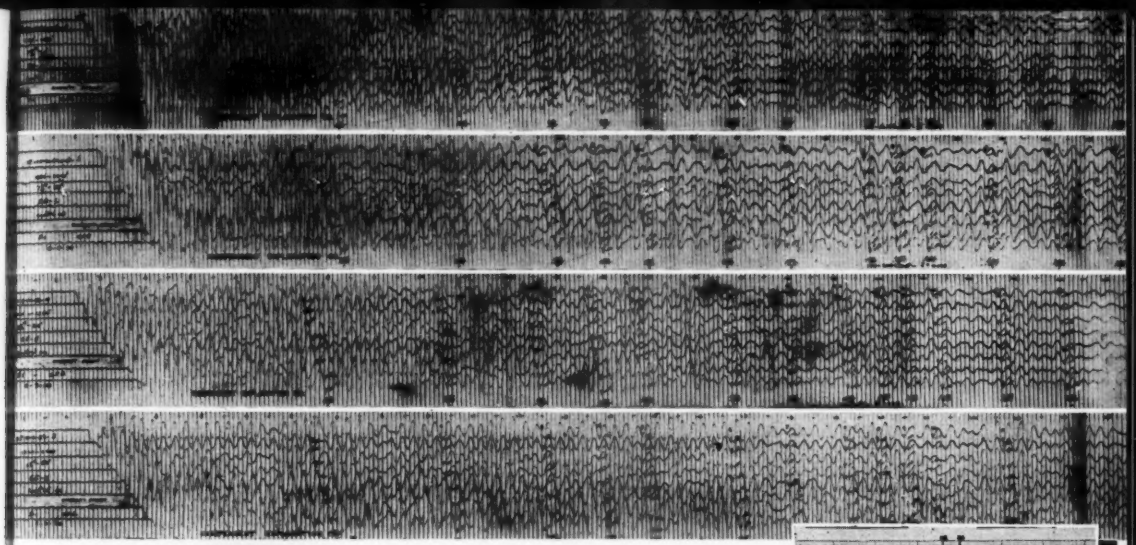

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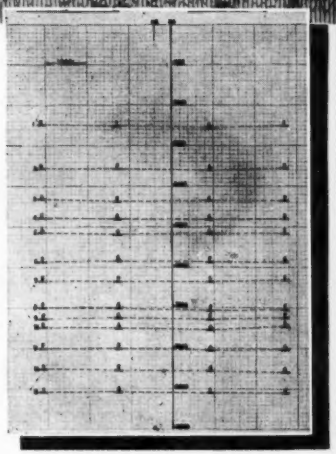

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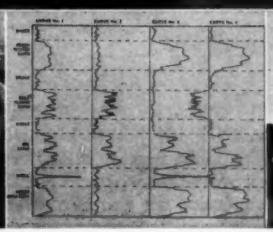

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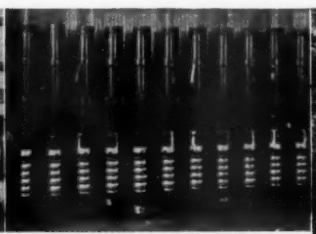

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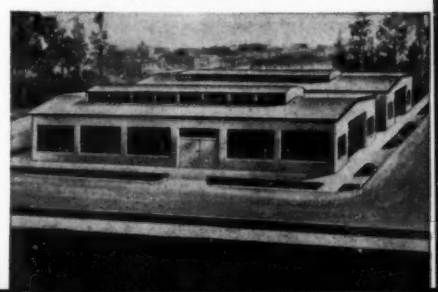

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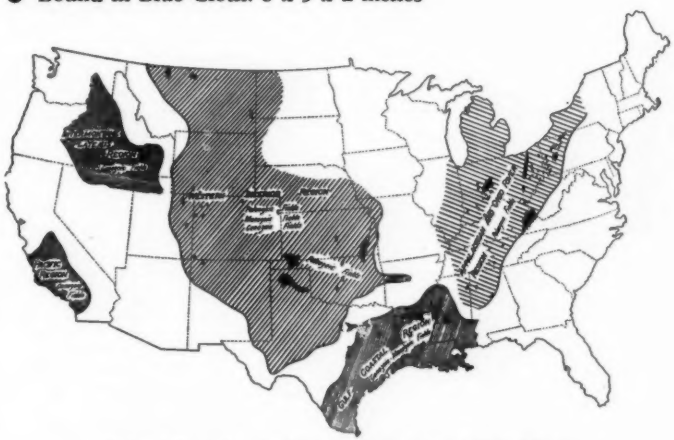

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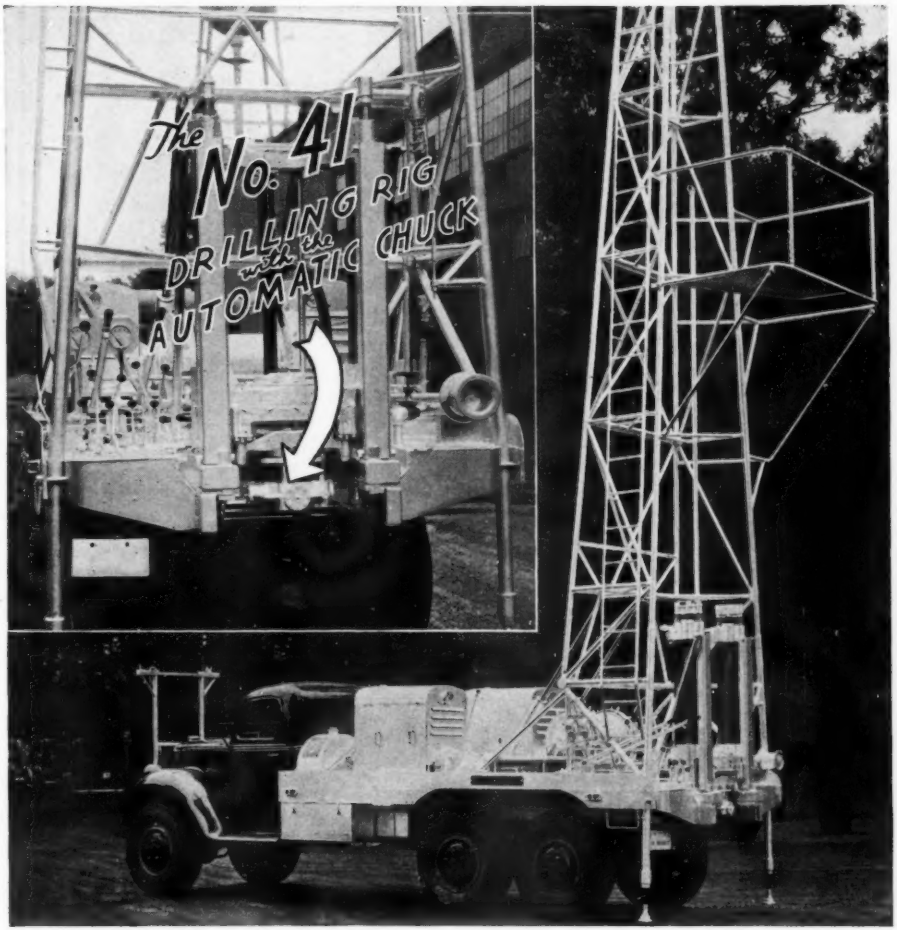

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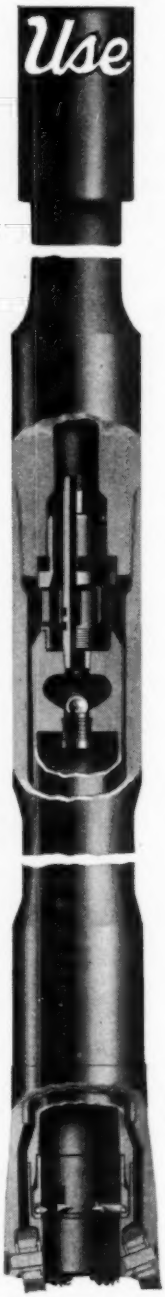

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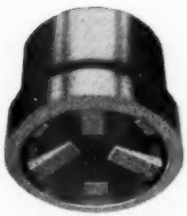

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